Joint CSCE Construction Specialty & CRC Conference 2025
Conférence conjointe spécialisée en construction de la SCGC et CRC-2025

Montreal, Quebec
July 28-31, 2025 / *28-31 juillet 2025*

BIM-DRIVEN AUTOMATED QUANTIFICATION OF MATERIAL REUSABILITY POTENTIAL IN BUILDING RENOVATION PROJECTS.

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ABSTRACT: (200-250 words)

The construction industry is a major contributor to global waste, with the United States generating six hundred million tons of construction and demolition waste in 2018 alone. This highlights the significant environmental challenges requiring immediate attention. The circular economy approach suggests a solution by focusing on waste reduction, reuse, and recycling of materials to enhance sustainability. While extensive research on material reusability exists, studies on renovation projects leveraging technology remain limited. To address this gap, this study develops an algorithm that automatically estimates materials in existing structures for various reusability options in renovation projects. After identifying key material reusability options, the authors selected a testbed project and evaluated these options by analyzing building materials and elements. They then developed an algorithm to calculate the material quantities for each reusability option and integrated it into a Building Information Modeling plug-in tool. By comparing automatic quantity take-off results with manual quantity calculations, they revealed a total volume difference of 1% between the two methods, demonstrating high accuracy and reliability. This study contributes to the body of knowledge on material reusability and building adaptation by introducing a novel automated material quantification tool. In addition, the developed plug-in tool helps project managers and designers assess the potential of material reuse during the design phase, facilitating informed decisions on selective demolition and improved waste management to support the sustainability and circular economy in the construction industry.

Keywords: Material Reuse; Automatic Quantification; Renovation Projects; Adaptive Reuse; Building Adaptation; Building Information Modeling.

1. INTRODUCTION

The construction industry is a significant contributor to environmental challenges, including global warming, natural resource depletion, waste generation, and emissions (Lu and Yuan 2011; Tatari and Kucukvar 2012; Minunno et al. 2020). This is largely driven by the industry's substantial usage of material in urban areas. Remarkably, approximately half of all materials mined globally are being transformed into construction materials (Choi et al. 2023). The building industry alone accounts for 32% of the world's resource depletion and 40% of the solid waste sent to landfills (Sanchez et al. 2019). The growing global population further

exacerbates these issues by increasing demand for housing and other built environments (Ginga et al. 2020), and such demand has resulted in excessive raw material depletion and a massive increase in construction and demolition (C&D) waste through rebuilding, construction, and expansion services (Aslam et al. 2020).

Therefore, the industry must prioritize more sustainable practices that promote better usage of material resources, such as adopting circular economy (CE) principles. A CE emphasizes reducing, reusing, recycling, and recovering materials and products to extend their lifecycle (Guerra 2020). By continuously looping resources into use and eliminating waste, CE practices in construction and demolition waste management can play a significant role in reducing the environmental impacts of the construction industry, promoting sustainable development, and advancing the circular economy implementation (Jahan et al. 2022).

Extensive research has been conducted to enhance sustainability by promoting CE principles and material reuse in construction projects. However, most existing studies primarily focus on material reusability and reuse of waste materials in the construction and demolition phases (Vefago and Avellaneda 2013; Akanbi et al. 2018; De Wolf et al. 2020; Guerra et al. 2020; Saeed et al. 2023; Balasbaneh et al. 2024; Jiang et al. 2024). Notably, none of these studies addresses material reusability within the context of building adaptation projects – a current gap in the literature. With a growing number of old building renovation projects currently underway or planned for the near future (Reindl, 2022; Adolphus 2023; Washington, 2023), these projects present unique challenges, such as integrating old and new materials, addressing structural constraints, and meeting preservation requirements, all of which complicate material reuse. Evaluating how material reusability can be effectively integrated into such projects is therefore critical for the sustainability of the built environment, making this an essential area for further research.

To address this gap, the authors expanded on their previous work by developing an algorithm to automatically quantify the material reuse potential of existing structures for renovation projects. The developed algorithm was then incorporated into a Building Information Modeling (BIM) software in a user-friendly format, which makes it accessible for practical application. This tool was validated by comparing the results with manual calculations, demonstrating a minimal error margin of 1% in total volume.

The theoretical contribution of this research lies in the automation of the quantification methods developed in the authors' previous study for assessing material reuse potential in historic renovation projects. . This approach advances the theoretical understanding of material reusability in the context of building adaptation and renovation projects by automating and integrating this method within a BIM environment. Additionally, this research provides practical contributions by introducing a user-friendly tool that assists project teams and designers in making informed decisions about design strategies and waste management practices during the early phases of construction renovation projects.

2. LITERATURE REVIEW

Material reuse is essential for promoting sustainability and advancing CE implementation in construction projects. Previous research has introduced various approaches to facilitate material reuse, which can be broadly classified into two main categories: (1) the development of principles or indices to support material reuse and (2) the use of BIM as a method to evaluate material reusability from existing structures. The first category encompasses studies such as Villalba et al. (2004), who introduced the recyclability index of materials (R) to evaluate the economic feasibility of disassembling a product. This index measures the recyclability potential of recovered materials and focuses on optimizing disassembly to maximize material recovery. However, it does not account for other critical design decisions, such as minimizing product cost or maximizing its lifespan.

Vefago and Avellanda (2013) proposed a concept of assessing the recyclability potential of materials and building elements at the end of their first life cycle. Their research demonstrated that conventional residential buildings constructed using traditional methods can achieve high recyclability. This finding supports the recyclability strategy as a sustainable practice in building design.

Another study by Forghani et al. (2023) surveyed over 170 industry professionals to examine the importance of design principles in relation to the reusability of building components. Their research findings revealed that nine technical design principles are highly significant for reuse practices. Also, they identified a notable difference in perspectives between demolition contractors and building designers regarding eight of these principles.

The second category of researchers leveraged BIM to evaluate the material reusability potential of existing structures. By developing a BIM-based Whole-life Performance Estimator (BWPE), Akanbi et al. (2018) evaluated the salvage performance of structural components of buildings during the design stage. This tool, which employs a mathematical modeling approach, was integrated into a BIM environment and tested with three design specifications. The results showed that building designs incorporating steel structures, demountable connections, and prefabricated assemblies produce recoverable materials with high reusability potential.

Honic et al. (2019) introduced a BIM-supported Material Passport (MP) method to evaluate the recycling potential and environmental impact of materials embedded in buildings. They also developed a stakeholder management framework to facilitate collaboration. Through a case study, they identified the main implementation challenges of the BIM-based MP as inconsistent data and a lack of collaboration between the various stakeholders.

A study conducted by Gordon et al. (2023) created a semi-automated assistive process for planning the deconstruction of building materials for reuse, utilizing technologies such as sensing and scanning, scan-to-BIM, and computer vision techniques. This method was tested in a real-world project to evaluate the feasibility of recovering individual building elements.

Lu et al. (2024) proposed a conceptual framework that employs a knowledge graph to evaluate salvage methods for building materials based on factors including material type, usage duration, weather conditions, and local policy. This framework integrates with BIM to automatically assess the condition of materials salvage. However, this study is limited to the development of a conceptual framework.

In summary, the reviewed literature on material reuse in construction projects highlights various approaches, including the development of tools or indices for assessing recycling potential and the application of advanced technologies to support material reuse. While these studies provide valuable insights, they predominantly focus on general construction and demolition phases or specific types of building components. However, a notable gap exists in the application of BIM to investigate material reusability within the context of building adaptation projects.

3. METHODOLOGY

Figure 1 outlines the overview of the research methodology, which consists of five steps. First, the authors adopted a material reusability framework for renovation projects developed in their previous study. This framework outlines various material reuse options and methods for quantifying the reusability of each option. Next, the authors selected a testbed project and created a 3D model of the building. This step was prioritized in this study because the potential for material reusability depends on the purpose of the renovation and the material used. After selecting the building, the authors analyzed the materials used in the building and their specific purposes. They then developed an algorithm to automatically calculate the quantities of materials associated with each material reusability option. This algorithm was then integrated as a plug-in tool into a BIM software. To validate the tool, the authors compared the automatic quantity take-off (QTO) generated by the tool with manual quantity calculations. The study focused on three common materials in the testbed project (i.e., wood, brick, and glass). Notably, only architectural and structural elements were considered, while mechanical, electrical, and plumbing (MEP) systems and furniture were excluded from the analysis.
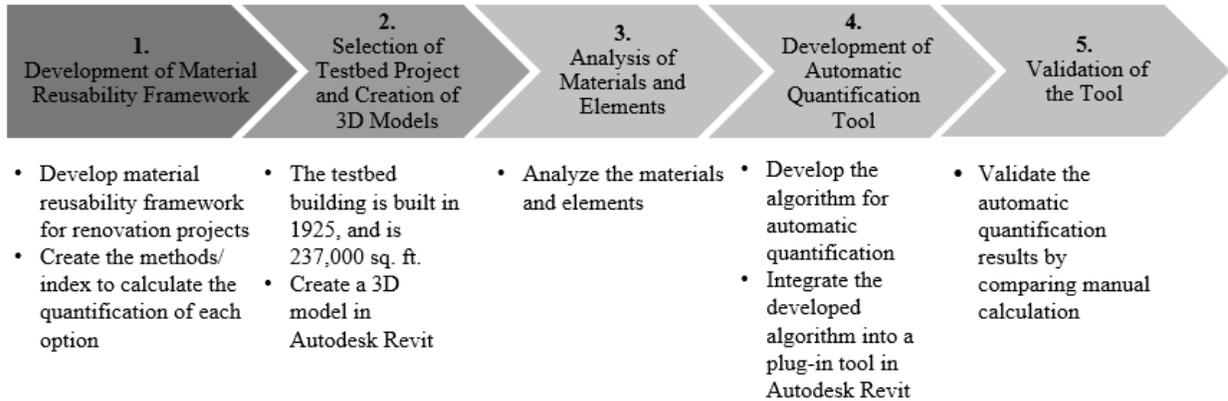
Figure 1: Research Methodology

4. MATERIAL REUSABILITY FRAMEWORK OVERVIEW

This study is built upon the authors' previous study, in which they developed a framework for material reusability for building renovation projects (Karim et al., ND). Figure 2 illustrates the framework developed. As shown, the process of identifying material reuse potential begins by assessing the current use of materials in the existing structure. Based on the material's condition and the scope of the renovation design, a decision is made to either retain or remove the materials. If materials are to be retained, they can either be preserved in their current state or repaired as needed. Conversely, if materials are to be removed, they can be hauled off-site and processed through one of four pathways: (1) recycling, (2) downcycling, (3) repurposing, or (4) landfilling. For example, exterior walls are often retained in renovation projects, either preserved as is or repaired to enhance functionality or aesthetics. Following the development of this framework, the authors focused on quantification methods for each reuse option. For the "Retain" category, the calculation for preservation and repair depends on the condition of existing materials and the scope of design work. For the "Remove" category, the authors referenced publicly available data from the United States Environmental Protection Agency (EPA) to derive the national average of recycling, downcycling, repurposing, and landfilling construction waste.
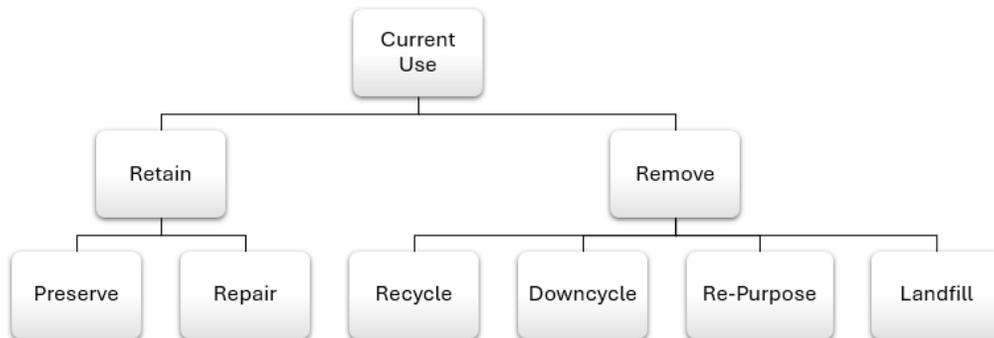

Figure 2: Material Reusability Framework (MFR) for Renovation Projects (Karim et al. NA)

5. SELECTION OF TESTBED PROJECT AND CREATION OF 3D MODELS

A historic building in the Midwest region of the United States was selected as a testbed project to apply the framework developed. The building was built in 1925 and has a total gross area of 237,000 square feet. This building was chosen for its historical significance, its status as closed for renovation, and the authors' access to the site for inspections. The creation of a 3D model involved two primary steps. First, due to the absence of available design drawings, the authors used a 3D scanner (i.e., Matterport Pro Camera) to

capture high-quality interior images of the building. These images were utilized to generate a 3D view model that provides the building dimensions and material information. Using this data, the authors developed a detailed 3D model in Autodesk Revit at the Level of Development (LOD) 300. LOD 300 was selected because it offers a detailed representation of the building, including precise dimensions, sizes, quantities, orientation, and location of elements. Notably, this LOD is commonly used by general contractors and industry practitioners and is suitable for accurately quantifying materials in the BIM model. To complete the process, material information was manually incorporated into the BIM model.

After selecting the testbed project, the authors analyzed the materials used in the building and their respective purposes. Given the era in which the building was constructed, they focused on three commonly used materials in the building: (1) wood, (2) brick, and (3) glass. Wood was used for both structural purposes (i.e., ceiling truss) and architectural features (i.e., doors and window frames). Glass was used for windows, and brick was used for interior and exterior walls. As abovementioned, the decision to "Retain" materials depends on the scope of the renovation work and the condition of the materials. Following an inspection by a general contractor who assessed the buildings for potential renovation, the authors identified the masonry exterior walls and wood trusses as suitable to be retained for the renovation projects. All other materials, including those used in interior walls, windows, and doors, were designated for removal. Table 1 summarizes the materials analyzed, their associated purposes within the building, relevant element details, and corresponding reuse options.

Table 1: Material Information

Material	Purpose	Element	Reuse Option
Wood	Architectural	Door, Window frame	Remove
	Structural	Truss	Retain – Repair
Brick	Architectural	Interior partition wall	Retain – Preserve
	Structural	Exterior load bearing wall	Retain – Preserve
Glass	Architectural	Window	Remove

6. DEVELOPMENT OF AUTOMATIC QUANTIFICATION TOOL

Using the information collected and analyzed in the previous sections, the authors developed an algorithm, which was then integrated into a plug-in tool for Autodesk Revit software to calculate the material quantities for each reuse option in a BIM model. The developed tool retrieves relevant data from the model through an embedded algorithm. The tool is designed to be used after the BIM model has been created and a comprehensive qualitative assessment of the existing structures has been completed. The tool integrates seamlessly into the Autodesk Revit software through a new option in the ribbon tools menu and is designed to be intuitive, requiring no formal training for effective use. This tool identifies the quantity of each material from the BIM model and multiplies it by the index created based on the EPA to determine the material quantities for each reusability option.

Figure 4 illustrates the tool. The tool automatically generates a list of relevant elements from the BIM model, streamlining the assessment process, and a user is prompted to select a specific element of interest to evaluate its material reuse potential (Figure 5). Based on the selected element, the tool provides a list of materials associated with the element. The user then selects a specific material of interest (Figure 6). In the next step, the tool prompts the user to decide whether the material will be retained in the building or removed from the existing structure. This decision is guided by the scope of work and the renovation design intentions for the project. Subsequently, the tool automatically converts the quantity from cubic meters (m³) in the BIM model to tons using the LEED waste conversion protocol, ensuring consistency with the EPA's waste management classification. Finally, the tool provides a detailed breakdown of the material quantities for each potential reuse option, including recycling, downcycling, repurposing, and landfilling (Figure 7). Figures 5, 6, and 7 show the screenshots of the developed plug-in tool integrated within Autodesk Revit.

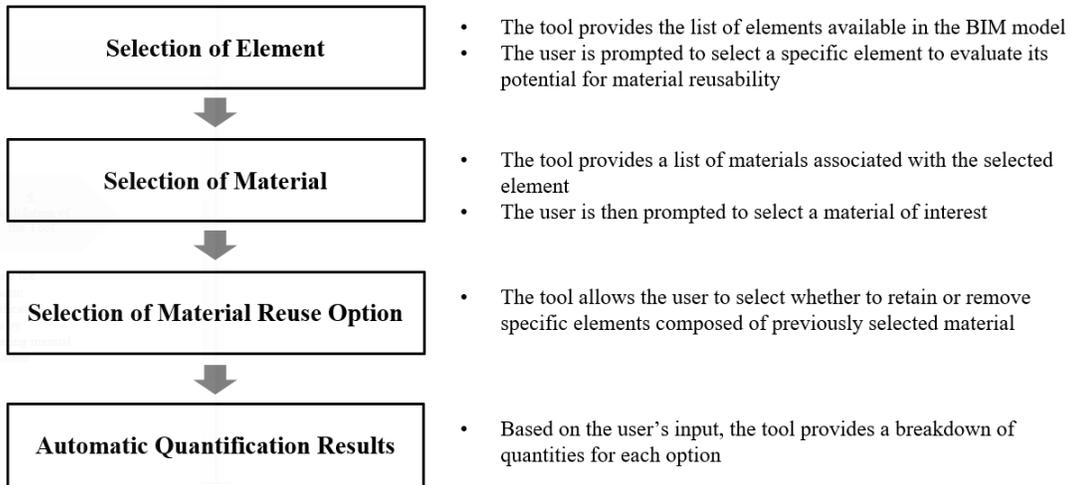| Selection of Element	• The tool provides the list of elements available in the BIM model • The user is prompted to select a specific element to evaluate its potential for material reusability
Selection of Material	• The tool provides a list of materials associated with the selected element • The user is then prompted to select a material of interest
Selection of Material Reuse Option	• The tool allows the user to select whether to retain or remove specific elements composed of previously selected material
Automatic Quantification Results	• Based on the user's input, the tool provides a breakdown of quantities for each option

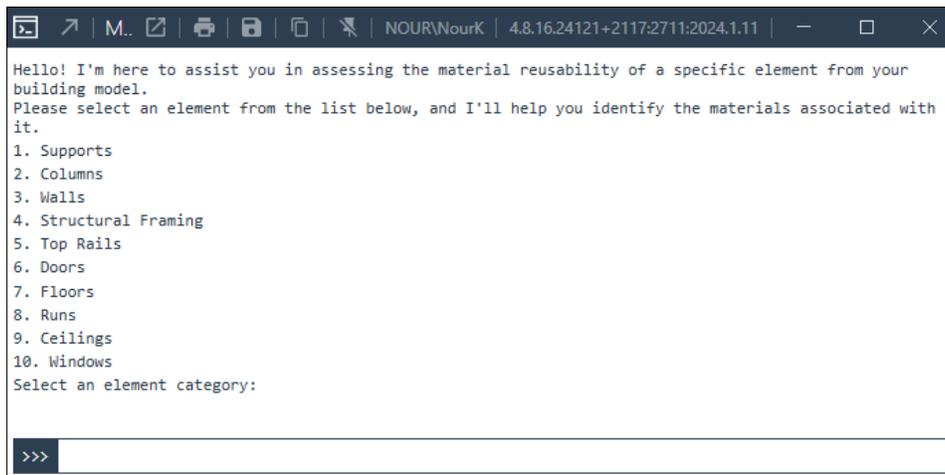Figure 4: Plug-in Tool Logical Flow

Figure 5: Step 1 of the Plug-in Tool in Autodesk Revit
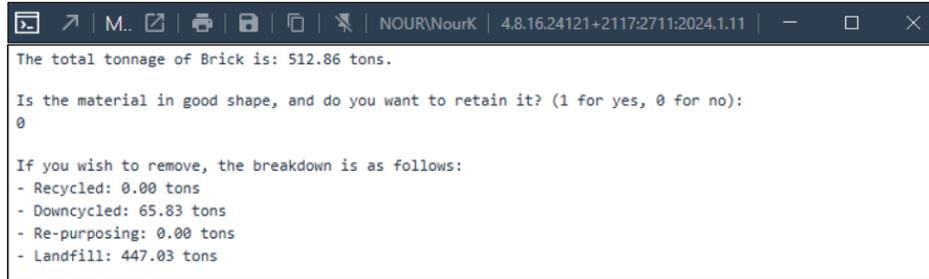

Figure 6: Step 2 of the Plug-in Tool in Autodesk Revit

Figure 7: Steps 3 and 4 showing the Final Results of the Plug-in Tool in Autodesk Revit

7. TOOL VALIDATION

The developed tool was validated by comparing the automatic QTO generated by the tool with manual calculation using the selected testbed project. Table 2 presents the results of this validation. The comparisons demonstrate a difference of approximately 1% in the total material quantification between the two methods. Notably, a discrepancy was observed in the QTO for windows, which may be attributed to the window and door dimensions being aggregated in a block format within the model under examination.

Table 2: Comparison between Manual and Automatic Quantification Take-Off

Material	Element	Quantification	
		Manual (tons)	Automatic (tons)
Wood	Door, Window frame	0.58	1.01
	Truss	1.11	1.11
Brick	Interior and exterior walls	512.87	512.86
Glass	Window	3.75	8.54
	Total	**518.31**	**523.52**

8. DISCUSSION

In this study, the authors demonstrated a novel approach to automatically quantify materials reuse potential in renovation projects leveraging their framework. Since material reuse in renovation projects differs from that in construction and demolition projects, this approach provides an effective way to estimate material quantities during the design phase of such projects. The following are key findings that emerged from this study.

First, the developed tool provides accurate material QTO. The tool operates by first extracting material quantities directly from the BIM model and then multiplying these quantities by a developed index to determine the amount of each material associated with different reusability options. Therefore, the accuracy of these estimates highly depends on the level of detail and the precision of material and element information in the BIM model. Notably, the organization of elements and materials is critical. For optimal results, elements of the same material should be grouped within the same family to ensure consistent material properties. This means all materials should be defined with no duplicates and consistent property assignments. In addition, the BIM model should be properly purged and cleaned. When the designers and project managers have a clear understanding of the scope of the work and design intentions, and when BIM models are produced with high LOD with accurate material and element information, this tool will generate highly accurate estimates. However, any inaccuracies or omissions in the BIM model will result in incorrect quantifications.

Second, this tool provides a ballpark estimate of material reusability potential during the renovation planning/design phase, which is typically challenging due to uncertainties in the existing structure, especially in renovation projects. By providing this early estimation, the tool assists in design decision-making, waste management planning, and sustainability practices in construction projects. It is also an effective tool for feasibility testing of material reusability in the early stages of projects.

Third, the developed plug-in tool is intended to be user-friendly within BIM software (i.e., Autodesk Revit). Operating similarly to a chatbot, the tool prompts users with questions at each step, and users provide answers to determine the material quantities of interest. This tool can be easily integrated into other BIM platforms for future projects.

There are some limitations to this study. First, this study is the usage of 2015's national average for material reuses from EPA construction and demolition data – which was the latest released. However, the developed algorithm can be easily customized by users to adjust the recycling, downcycling, repurposing, and landfilling percentages according to their own standards. Also, the tool is currently designed with a specific software, Autodesk Revit. However, we recognize the importance of the extensibility of the tool in AEC as teams use various tools in their day-to-day workflows. The tool can easily be adapted to other BIM platforms with minor adjustments to its coding language to align with the data storage and extraction logic of these platforms.

9. CONCLUSION

Sustainability practices and CE principles have gained increased attention in the construction industry due to the significant environmental impact of construction and demolition waste. While prior research has focused on material reuse in the construction and demolition phases, there remains a gap in studies addressing material reuse potential in renovation projects. As the number of renovation projects continues to rise, integrating sustainable approaches into these projects becomes crucial. To address this gap, this study presents a novel approach for the BIM-driven automated quantification of material reusability potential in building renovation projects. Building on the material reusability framework for renovation projects developed in the authors' previous study, an algorithm was created and integrated into a plug-in tool in BIM software, Autodesk Revit. This tool guides users through a series of questions to determine the quantities of material selected for each reuse option. The tool was validated by comparing its automatic quantity take-off results with manual calculation, revealing minimal discrepancies, with a total volume difference of 1%. This study found that when BIM models are created with high levels of detail and accurate material and element data, the tool provides highly reliable results. In addition, the flexibility of the developed tool allows users to customize reuse percentages based on their own standards, enhancing its applicability across various renovation projects.

In conclusion, this study makes a significant academic contribution by introducing a novel automated tool for quantifying material reusability in building renovation projects. By bridging the gap between theoretical framework and practical applications, it provides a robust method for estimating material quantities during design phase. Moreover, it supports project teams and designers in making informed decisions regarding design and waste management, ultimately advancing sustainable practices in building renovation projects.

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