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A Comparative Review of Sustainable Building Approaches: Energy Efficiency, Embodied Carbon, and BIM-LCA Integration

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ABSTRACT:

The construction of building uses a lot of energy and natural resources. One important type of energy in the process is embodied energy, which means all the energy used to make, transport, and build materials, and also to maintain or demolish the building later. To understand how much energy a building really uses, we can study it through Life Cycle Assessment (LCA). LCA helps to measure the total energy and environment impact from the beginning of construction to the end of a building's life. By using LCA, builders and designers can choose better materials and methods that use less energy. Using local, recycle, and eco-friendly materials can greatly reduce embodied energy. This approach helps make building more sustainable and support the goal of creating energy-efficient and low-carbon buildings for the future.

Key Words: Energy efficiency, Embodied carbon, Life Cycle Assessment (LCA), Building Information Modeling (BIM), Sustainable construction, Autodesk Revit, One Click.

INTRODUCTION:

Building use a large amount of the world's energy and release a big part of greenhouse gages. With the growth of cities an population, need for houses and infrastructure has increased. Earlier, most studies and designs focused only on operational energy. It is the energy used for lighting, cooling, and heating during the building's use. But now, embodied energy and embodied carbon, which come from making and transporting building materials and construction work, are also seen as very important parts of a building's total environmental impact.

To achieve global goals like net-zero energy and carbon, we must look at the entire life cycle of building from the making of materials to their disposal. One useful method for this is Life Cycle Assessment (LCA), which helps measure the environmental impacts at every stage of a building's life. Along with this, Building Information Modeling (BIM) has become a powerful digital tool that allows designers and engineers to create 3D models, calculate materials, and test different design options. When BIM and LCA are used together, they make it easier to choose materials and designs that reduce carbon emissions and energy use.

Even with these advanced tools, many designers still focus mainly on operational energy. There are challenges like lack of proper data, poor connection between software tools, and less awareness about the effect of embodied carbon. In earthquake-resistant (seismic) design, strong materials are needed for safety, but they often increase embodied carbon. Similarly, prefabrication building can reduce waste and time, but their carbon benefits are not always fully studied. Also, how people live and use energy in buildings can change the total performance a lot, yet this is often ignored. These problems show the need for complete studies that combine technology, materials, and human behavior.

The main aim of this study is to review and connect different research papers that focus on improving energy efficiency and reducing embodied carbon in buildings. It seeks to understand how modern tools like BIM and LCA can work together to make better design decisions. The study also aims to compare the different methods used by researchers, highlight the shift from focusing only on operational energy to including embodied energy, and suggest ways to design buildings that are both energy-efficient and environmental friendly. Overall, the objective is to provide a clear understanding of how building design, materials, and digital tools can work together to achieve sustainable and low-carbon construction.

LITERATURE REVIEW:

Noha Ahmed Mohamed, N., El-DashK. M., Attia, T. M., & Abdel-Monem, M. (2023) studied how different types of building envelope design can improve a building's energy efficiency. The authors explained that the building envelope, which includes walls, roofs, windows, and insulation, plays a big role in controlling heat flow and indoor comfort. They tested several design alternatives with different insulation materials and window sizes using simulation software. The authors found that improving insulation and optimizing window orientation can reduce the building's total energy use by around 20-25%. They explained that choosing the right envelope design at the early design stage can lead to big energy savings and improve thermal comfort for users.

Suwondo, R., Keintjem, M., & Cunningham, L. (2024) focused on how to design earthquake-resistant building that are also environmentally sustainable. The authors studied concrete moment-resisting frames, which are common earthquake-prone areas, and calculated how much embodied

carbon these structures release during construction. They used life cycle assessment (LCA) tools to measure the carbon footprint of different structural designs. The authors explained that although stronger frames improve safety, they also increase embodied carbon because of the larger amount of steel and concrete used. Their results showed that using low-carbon materials and hybrid concrete-steel system can balance safety and sustainability. The authors concluded that seismic design should include both structural strength and environmental performance.

Ge, S., Zhang, X. (2023) developed a system that combines Building Information Modeling (BIM) and Life Cycle Assessment (LCA) to predict and reduce embodied carbon in prefabricated buildings. The authors explained that prefabricated construction can save time and reduce waste, but designers need accurate data to measure its real carbon impact. Their system automatically takes material data from the BIM model and connects it with LCA databases to calculate embodied carbon in real time. The study showed that this method reduces calculation time and helps designers choose better materials and construction methods. The authors highlighted that this integration makes sustainability assessment faster, more accurate, and useful in early design stages.

Ajayi, S. O., Oyedele, L. O., & Ilori, O. M. (2019) examined how the importance of embodied energy changes depending on what materials and energy source are used in buildings. The authors compared buildings that use traditional materials with those that use more sustainable materials and renewable energy system. They explained that as building start using renewable energy, operational energy (used during use) becomes smaller, while embodied energy (used during construction) becomes more important. Their result showed that in low energy buildings, the embodied part can make up most of the total energy use. The authors conclude that designers should not only focus on operational energy but also consider embodied energy when selecting materials and planning construction.

Ma, L., Azari, R., & Elnimeiri M.(2024) conducted a detailed case study using BIM and LCA to measure the embodied carbon and environmental impacts of high-rise buildings. The authors used software tools such as Revit and Tally to analyze three types of structures steel, concrete and composite. They explained that steel structure, while lighter, usually have higher embodied carbon because of the energy used in producing steel. Concrete, on the other hand, has a lower carbon footprint per unit but more total mass. By using BIM, they were able to calculate material quantities more precisely and visualize carbon emissions at each stage. The authors concluded that using BIM and LCA helps engineers make better structural decisions and design more sustainable tall buildings.

Monteiro, H., Fernandez, J.E. and Freire, (2016) compared the total life cycle energy use of a new energy- efficient house and an older existing house. The authors explained that they wanted to see how much occupant behavior and building system affect total energy performance over a long period. They used life-cycle assessment methods to include both embodied and operational energy. Their results showed that even though the new house was designed to be efficient, the way people used it (for example, heating and cooling habits) had a big effect on actual energy use. The authors concluded that designed low-energy buildings is not enough educating occupants and managing building system properly are also important for real energy savings.

CONCLUSION:

This review underscores that improving building sustainability required a balanced approach integrating design innovation, material efficiency, and digital assessment tools. Energy- efficient envelopes reduce operational energy, while BIM-LCA frameworks enhance embodied carbon evaluation accuracy. Structural and material choices must align with seismic and environmental goals. Furthermore, occupant behavior remains a crucial factor realizing projected energy savings. Collectively, these studies demonstrate that sustainable design in multi-dimensional technological, behavioral, and systemic and the integration of BIM with LCA represents a vital step toward achieving low-carbon, high- performance buildings. By using BIM-LCA systems, choosing low- carbon materials, and promoting efficient energy habits, the building industry can move towards greener, smarter, and more sustainable buildings.

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