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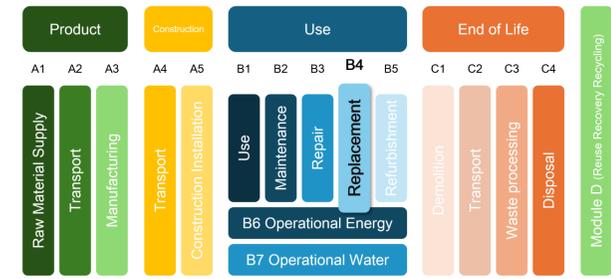
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## Introduction

Life cycle assessment (LCA) has become a core tool for evaluating the environmental performance of buildings, particularly in the context of global carbon neutrality targets. While substantial attention has been given to upfront embodied carbon and operational energy use, emissions associated with the replacement of building components during the use phase (Module B4) remain insufficiently addressed. As buildings age, components such as façades, finishes, and mechanical, electrical and plumbing (MEP) systems are replaced multiple times over the building lifespan, leading to a cumulative carbon impact that can no longer be considered marginal.

Current LCA standards, including EN 15978 and ISO 21930, acknowledge the relevance of replacement-related emissions but provide limited methodological guidance on how they should be quantified. In practice, many studies rely on simplified assumptions, fixed service-life values, or software defaults that fail to reflect real-world variation in component durability, usage conditions, and environmental exposure. This lack of structure reduces transparency, limits comparability across studies, and risks underestimating long-term embodied carbon, particularly for components with short service lives or high replacement intensity.



## Methods

To address the lack of structured methods for quantifying replacement-related emissions in building LCA, this study proposes a modular framework for estimating carbon emissions from building component replacements (Module B4). The framework integrates Reference Service Life (RSL) with a context-sensitive Estimated Service Life (ESL) approach, enabling systematic, component-level calculation of replacement emissions across multiple cycles within a defined study period.

First, a comprehensive Reference Service Life (RSL) database was established by synthesizing information from international standards, industry guidelines, and academic literature. This database provides baseline service-life values for a wide range of building components and serves as a consistent reference for early-stage lifecycle assessment when project-specific data are unavailable.

Second, an enhanced Estimated Service Life (ESL) calculation method, termed the Guided Factor Method (GFM), was introduced to adjust RSL values according to project-specific conditions. The method consolidates key influencing parameters into five factors, including design and specification quality, usage environment, outdoor environment, work execution level, and maintenance level. Each factor is assigned through predefined reference ranges, reducing subjectivity while allowing flexibility to reflect contextual variation. The modular structure of the method enables staged application, supporting both early design assessments and post-construction refinement.

Finally, a B4-phase replacement carbon emission calculation equation was formulated to quantify emissions associated with each replacement cycle. For each component, the number of replacements over the building lifespan is determined based on its ESL, and emissions from production (A1–A3), construction (A4–A5), and end-of-life processes (C1–C4) are aggregated accordingly. Optional Module D benefits from recycling or recovery are calculated separately to maintain consistency with EN 15804 system boundaries. Together, these steps form a scalable and transparent framework for assessing long-term replacement-related carbon emissions in building LCA.

## Conclusion

This study demonstrates that replacement-related emissions (Module B4) constitute a substantial and non-linear component of long-term embodied carbon in buildings. Based on a BIM-integrated case study of Snowdon Tower, a mid-rise mixed-use building evaluated over 60- and 100-year study periods, results show that B4 emissions reach approximately 45% of initial production emissions at 60 years and grow to nearly equivalent levels over a 100-year lifespan, highlighting the critical importance of accounting for component replacements in whole-building LCA.

The proposed modular framework integrates Reference Service Life with a Guided Factor Method-based Estimated Service Life, enabling more realistic modeling of replacement cycles under varying use and environmental conditions. Results further reveal that carbon-intensive façade systems and short-lived MEP components act as dominant long-term emission drivers, with replacement impacts accumulating in discrete renewal waves rather than linearly over time.

By providing a structured, transparent, and scalable approach to B4-phase assessment, this framework addresses a key methodological gap in current LCA practice and supports more informed design and policy decisions aimed at long-term carbon reduction.

