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Comparative whole-building life cycle assessment of renovation and new construction

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ABSTRACT

Renovation of existing buildings has been identified as a major strategy for reducing the environmental impacts associated with building construction. From the perspective of embodied impacts, repurposing existing structures can reduce the amount of new materials that have to be extracted, manufactured, and installed. While the literature on energy efficiency retrofitting is relatively abundant, a smaller number of studies investigate the differences in whole-building embodied impacts of major renovations. This study presents an approach for conducting a whole-building life cycle assessment (LCA) on building renovation projects, suggests an approach for conducting comparative assessments between renovation and new construction, and demonstrates the approach on an adaptive reuse case study. The approach consists of comparing the full life cycle impacts of the existing building to the sum of the life cycle impacts of the components added in the renovation and the maintenance and replacement needs of the existing/reused components. The case study showed 53–75% reductions across 6 different environmental impact categories when the renovation was compared to a new construction scenario. The reuse of the structural and envelope components provided the majority of the reductions, as most of the renovation was of the interior components and finishes. The presented work can be used as a model for consistent LCAs on other renovation projects and to show designers, policy makers, and building owners the environmental benefits of adaptive reuse over new construction as a result of reduced need for new building materials.

1. Introduction

The environmental impacts of buildings have been under major scrutiny over the past few decades [1,2]. Life cycle assessments (LCA) of buildings reveal that the global warming potential (GWP) associated with the energy used to operate a building typically accounts for the majority of the total environmental impacts [2–4]. Studies also reveal that improving the energy efficiency of building operations and using more renewable energy sources can significantly reduce the operational energy use impacts [5–7]. Scientists and designers are -also focusing on improving assessment methods and strategies aiming to help reduce the environmental impacts of building material production, also called embodied impacts [2]. One frequent suggestion for reducing embodied impacts is to focus on the renovation, retrofit, and adaptive reuse of existing buildings [8–11]. While the life cycle benefits of renovations are clear, there is a lack of uniform guidelines for LCA practitioners on how to conduct LCA on renovation projects and how to perform a comparative assessment between renovated buildings and analogous newly constructed buildings [12,13]. This inhibits the effectiveness of using LCA to quantify the environmental benefits of renovations and to understand the scale of renovation benefits in practice [14]. Defining clear language applicable to renovations can make it easier for practitioners to conduct such assessments and defining a scope more aligned with whole-building LCA for new construction can make comparisons across projects easier and more consistent. Aligning scopes can also be important for comparisons to any future building LCA benchmarks similar to the Commercial Buildings Energy Consumption Survey (CBECS) and Department of Energy Reference Buildings used for benchmarking energy models.

The terms retrofit, refurbishment, renovation, and reuse of buildings are often used interchangeably. Retrofit typically means addition of features for the improvement of performance in a particular area (e.g., energy efficiency or structural integrity) [15], and is not the focus of this study. Refurbishment and renovation both represent a

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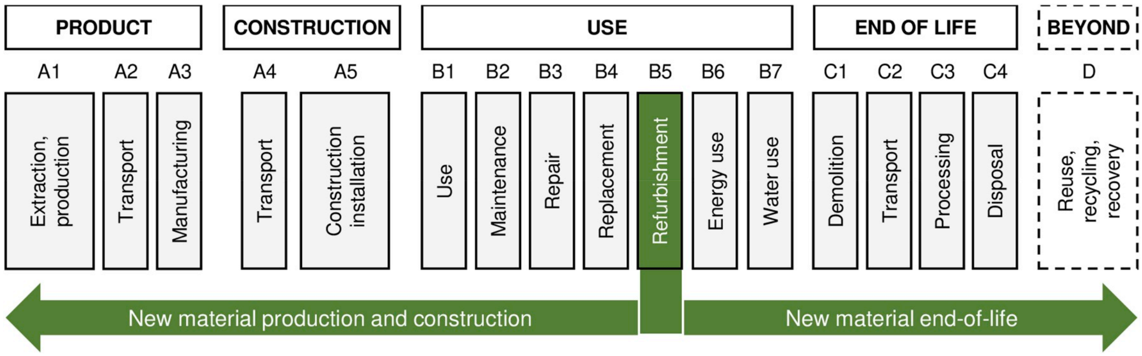

Fig. 1. Building life cycle stages and modules adapted from EN 15978 [16].

"modification and improvement to an existing building in order to bring it up to an acceptable condition" [16]. The International Organization for Standardization (ISO) 21931 [17] and European Standards (EN) 15978 [16] both use the term refurbishment, while the term renovation is more prevalent in the North American region and is used throughout the Leadership in Energy and Environmental Design (LEED) reference manual [18]. The term renovation is used throughout the rest of this study. Additionally, adaptive reuse, a term related to the presented case study, is a form of building renovation with the element of transforming a building of particular use to a different use type (e.g., transforming a factory into an office building).

The ISO 21931 and EN 15978 standards cover renovation but provide a limited description of its scope and implementation, resulting in multiple possible interpretations. EN 15978 defines the renovation substage as part of the use stage (shown in Fig. 1 as module B5), which includes any major technical or functional changes to a building that are not part of routine use and maintenance, or predictable repair and replacement. According to the standard, the boundary description of module B5 should include the following:

- Production of new components of the building [Modules A1-A3]
- Transport of new components (including the production of materials lost during transport) [Module A4]
- Construction and waste management as part of the refurbishment process (including the production of materials lost during the refurbishment) [Module A5]
- End-of-life (EOL) of the substituted building components [Modules C1–C4]

The EN 15978:2011 standard lacks clarity on what constitutes the "waste management of the refurbishment process" and "end-of-life of substituted building components" [16]. It is not specified if the waste management of refurbishment processes should include only the waste from the production and installation of newly added components or if it should also include the waste resulting from the demolition of existing components. Nor is it specified if the end-of-life of the substituted building components should include only the EOL (Module C) of the newly added components or also the EOL (Module C) of the demolished components.

To avoid ambiguities in the rest of this study, we first define the following life cycle stages within the life cycle of building renovation projects. We put forth our recommendation in Fig. 6 (also labeled in Fig. 2):

- Existing Product and Construction Stage: The initial product and construction stage (Module A) of the building intended for renovation.
- Existing Use Stage: Use stage (Module B) of the building intended for renovation that occurs prior to the renovation.
- Existing EOL Stage: End of life stages (Modules C/D) related to partial building demolition during the renovation process.
- Reused Use Stage: Use stage (Module B) within the boundary of the renovated building related to the use, repair, maintenance, and replacement of retained or reused components after renovation occurs.
- Reused EOL Stage: EOL stages (Modules C/D) within the boundary of the renovated building related to the demolition and disposal of retained or reused components after renovation occurs.
- New Product & Construction stage: Product and construction stage (Module A) of the newly added components during the renovation process.
- New Use Stage: Use stage (Module B) within the boundary of the renovated building related to the use, repair, maintenance, and replacement of the newly added components after renovation occurs.
- New EOL Stage: EOL stages (Modules C/D) within the boundary of the renovated building related to the demolition and disposal of the newly added components at the end of the building life.

Previous LCA studies of renovation and retrofit projects have often chosen varying boundaries and scopes depending on the studies' objectives. For example, there are many studies that have used LCA to understand tradeoffs in implementing operational energy efficiency improvements to existing buildings [19–23] (these are considered energy retrofits). These studies typically assess the environmental impacts and embodied energy of the additional components added to existing buildings (e.g. added insulation, more efficient windows, etc.) and compare them to the reductions in impacts and energy use as a result of the operational energy efficiency improvements. In other words, most energy retrofit studies compare the New Product and Construction stage and the New Use stage together with the new operational energy use and compare it to the original building's operational energy use before the energy retrofits. These studies typically ignore any components that are not related to the energy retrofit based on the assumption that they remain unchanged and therefore have identical impacts. This approach allows investigators to determine the payback time of energy improvements from an embodied energy and environmental impact perspective [19,24,25]. Similarly, some researchers have looked at the benefits of structural retrofits in seismically active regions, assessing the reductions in life cycle environmental impacts as a result of improved durability and lower probability of damages over a building's life [26,27]. Full-building LCAs studying differences between the environmental impacts of renovation and new construction comprehensively are less common and typically do not follow the same clear-cut approach.

Vilches et al. [25] recently reviewed literature on the varying definitions, boundaries, scopes, and analyzed building types in LCA studies of building renovation. The authors concluded the existing product and construction stage (A) and the existing use stage (B) are typically excluded, except where the existing components are reused (i.e. Reused Use Stage – B, as shown in Fig. 2). The New Product and Construction

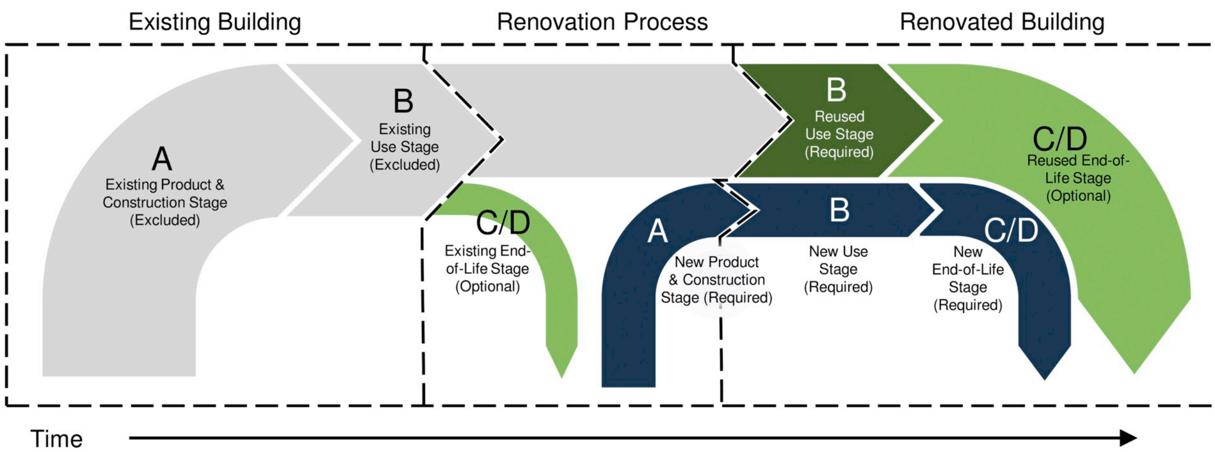

Fig. 2. Renovation LCA stage and boundary diagram. Recommendations for excluded, required, and optional stages are based on Vilches et al. [25].

(A), New Use (B), and New EOL (C) stages are typically included. Vilches et al. [25] also identified the option to further extend the boundary for the Existing EOL Stage (C) (i.e. waste management of selective demolition), and for the Reused EOL Stage (C) (i.e. waste management of retained existing components at the end of their useful life).

A closer look at three seminal studies comparing the whole-building embodied impacts of renovations with new construction scenarios show many different boundary selections for the comparisons. Frey et al. [9] assessed seven building types across four locations with a focus on understanding the embodied environmental impact benefits of renovation versus new construction. This study used an "avoided burden" approach for the comparison, which treats embodied impacts in existing buildings as a "sunk cost" from the past eliminating the need for new materials in the present. This means that in both the renovation and new construction scenarios, the full life cycle of only new components was included and any of the reused components in the renovation scenario were excluded. The study also included the selective demolition in the renovation scenario and the full demolition in the new construction scenario (i.e., Existing EOL stage in both scenarios). This approach was taken to capture the renovations' lower demand for new materials and the lower burden associated with the disposal of the existing buildings during the renovation process. A diagram showing the study's comparison of the renovation scenario and new construction scenario is shown in Fig. 3.

A similar approach was taken by Rønning et al. [28] in their study aimed at understanding the burdens or benefits of renovating a building for the Norwegian Bank headquarters, except this study excluded the future end-of-life disposal of both the renovation and new construction scenarios (i.e., the New EOL and Reused EOL stages), as shown in Fig. 4. The study included the existing building's demolition (i.e., the Existing EOL stage) in both scenarios, be it partial or full demolition. This is also the only known comparative LCA study that included the Reused Use Stage maintenance and replacement (B) in the renovation scenario in order to capture the additional maintenance and replacement needed for the reused components.

Researchers from the Athena Sustainable Materials Institute conducted a study comparing renovation versus new construction impacts for a building at the University of British Columbia [29]. The investigators took a similar approach to Rønning et al. [28], except they further reduced the study boundary to include only the existing building partial or full demolition (i.e., Existing EOL stage in both renovation and new construction scenarios) and the new building's New Product and Construction stage (A); excluding the New and Reused Use stages (B) and the New and Reused EOL stages (C) of the new building (see Fig. 5). The investigators took this approach because they were interested only in the impacts related to the renovation process, and not the whole life cycle.

The approach proposed in this paper is recommended for conducting whole-building LCA on renovation projects to create a model for consistency and transparency in accounting for the benefits of building renovation. The approach uses clearer terminology than previous approaches for differentiating between life cycle stages of renovation projects and it defines a scope for whole-building renovation LCA that is consistent with the scope of whole-building LCA typically

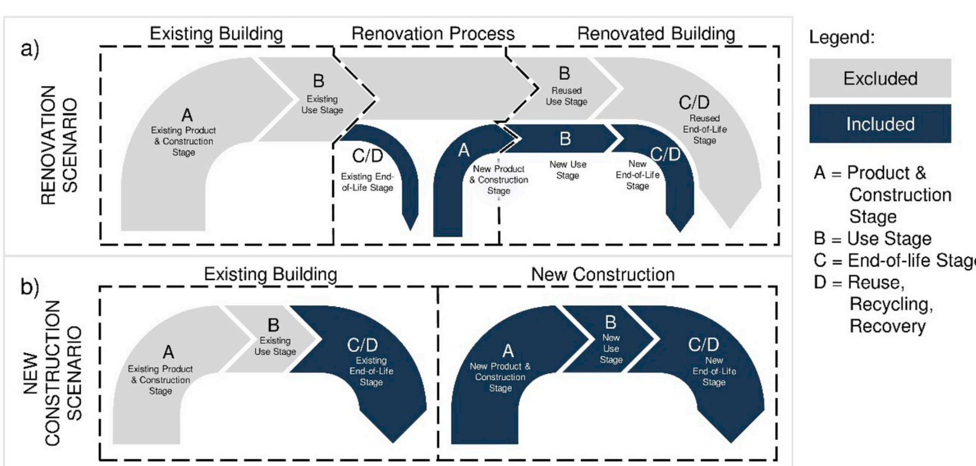

Fig. 3. Comparison of (a) renovation vs. (b) new construction scope are based on Frey et al. [9].

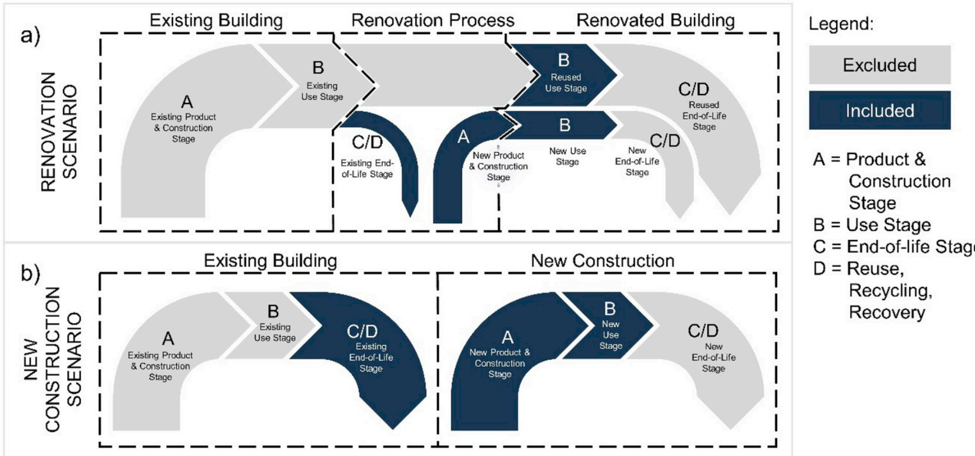

Fig. 4. Comparison of (a) renovation vs. (b) new construction scope are based on Rønning et al. [28].

used for new construction projects. The results of the case study, although specific to the described scenario, show the potential benefits of building renovation (specifically adaptive reuse) over new construction and pinpoint the major areas where reductions can be achieved.

2. Materials & methods

The new terminology used to describe individual life cycle stages related to LCA of building renovation (Fig. 6a) is inherently more complex than the terminology used to discuss the new construction scenario (Fig. 6b), since there are no overlaps between the boundaries of the existing building and the new construction in the new construction scenario. All components are therefore identified as either Existing or New, based on whichever boundary they are within. The same approach to conducting a whole-building LCA can be used for projects that are developed on an "occupied lot" (i.e., where existing development is being fully demolished to create space for the new construction, as shown in Fig. 6b) or "empty lot" (i.e., previously undeveloped land, as shown in Fig. 6c).

The product and construction stage (A) and end-of-life stage (C) of any new components should be captured in all scenarios [16], including renovation and new construction. Most studies have been excluding any life cycle stages related to reused components in the renovation scenario based on the avoided burden approach; however, based on Vilches et al. [25] interpretation of the EN 15978 standard [16], at least the use stage (B) of the reused components should also be attributed to the impacts of renovation, as the prolonged life of the building may result in additional use, maintenance, repair, and replacement impacts of the reused components. The recommended approach for assessing renovation impacts in comparative studies is, therefore, to include modules A-C of newly added components together with module B of the reused components, as shown in Fig. 6a.

The main reason for excluding the Existing EOL stage (i.e., partial demolition of the existing building) from the scope selection in the renovation scenario in Fig. 6a is to be consistent with the scope of whole-building LCA in a new construction scenario (Fig. 6b). Assuming the new construction scenario does not include disposal of an existing building (either due to lack of available information about a previous building or for new construction on empty lot), one cannot include Existing EOL stage in the renovation scenario without having an unequal scope.

Another reason for excluding the Existing EOL stage in the renovation scenario, as well as in the new construction scenario, is to avoid penalizing the renovation and new construction projects for decisions outside of their power. In other words, the new owner and designers likely did not have an opportunity to influence the selection of materials of the existing buildings, which in turn affects the possible disposal scenarios for those materials. The renovated building could therefore be penalized for related impacts without having many opportunities for their avoidance. That is not to say that the selection of the best disposal scenarios for those components should be disregarded; instead, it could be considered as part of a separate assessment

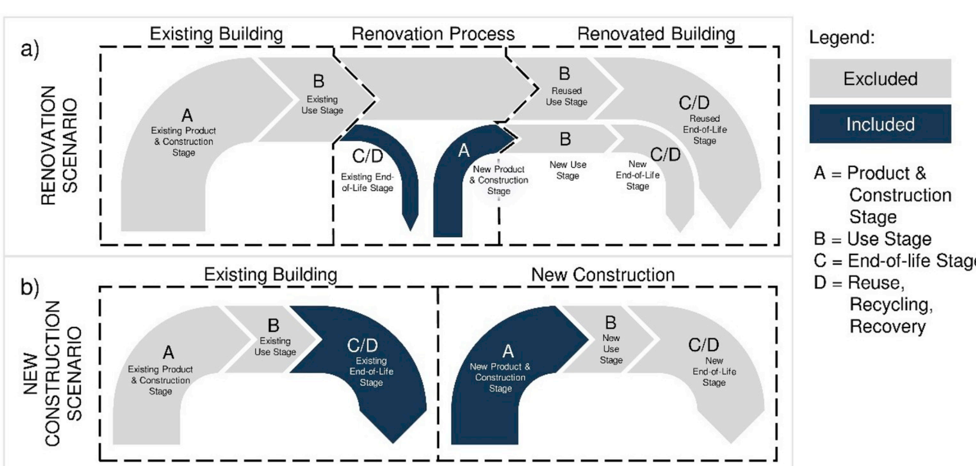

Fig. 5. Comparison of (a) renovation vs. (b) new construction scope based on the Athena study [29].

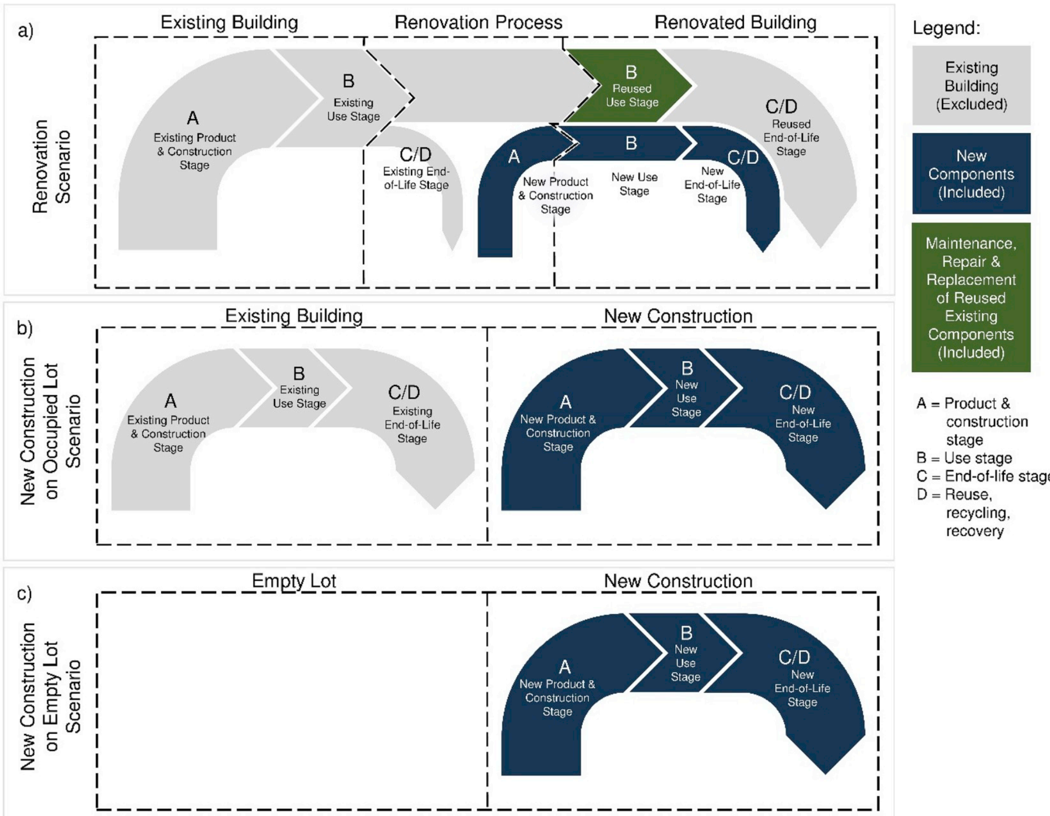

Fig. 6. Recommended scope for comparative LCA of (a) renovation scenario to (b) new construction scenario.

evaluating the best disposal options for those components.

The Reused EOL in the renovation scenario (Fig. 6a) is excluded because it also stems from the material selection of the previous building and would be equivalent to the Existing EOL stage in the new construction scenario. However, it does not mean that all disposal of reused components is excluded, as any material disposal related to the maintenance and replacement of the reused components should be captured in the Reused Use stage (B) [16].

3. Case study

To demonstrate the strength of the proposed approach, we conducted a whole-building LCA of a case study adaptive reuse project and compared it to an equivalent new construction scenario. The following section discusses the goal and scope of the assessment, inventory collection, and results and interpretation of the case study. The case study validates the proposed approach and provides a model for future studies comparing renovation to new construction while also highlighting the benefits of renovation over new construction.

3.1. Goal and scope of assessment

The primary goal of this case study is to analyze the environmental impacts of a building renovation project and compare its impacts to a hypothetical new construction scenario. The case study building was a 2-story, 5,500 m^2, stand-alone building located in an urban setting in Philadelphia, PA. It was built in 1948 as a beer bottling plant, warehouse, and shipping facility. Its construction system includes a braced steel frame infilled with concrete floors wrapped in a multi-wythe, non-load bearing masonry envelope. The building was used for its original purpose until 1980 when the beer bottling operation ceased, and the building was mostly unused for the next 30 years. In 2013, it was acquired by an architecture firm which repurposed the building as their new office and work shop. The firm reused as much of the original building as possible, including its structural system (steel columns, beams and roof trusses), concrete floor, and brick and terracotta envelope, and selected terracotta interior partitions. Some of the main changes during the renovation included a full replacement of windows, full replacement of roof thermal and moisture layers, and the addition of raised access floors and interior partition walls.

The architectural firm required space for individual work areas, model fabrication lab, small and large meeting rooms, storage, and parking. The functional unit for the comparison is 1 building providing the work and support space (about 5,500 m^2) for the architectural firm consisting of approximately 125 employees for 60 years. The scope of the assessment included the life cycle stages and building systems shown in Fig. 7. This study focused on assessing environmental impacts related to the use of building materials, and, therefore, excluded the construction installation (A5), use (B1), and demolition (C1) stages primarily consisting of labor and equipment use. The operational energy use (B6) and operational water use (B7) stages were also excluded for the same reason.

3.2. Inventory analysis

The existing building was laser scanned and uploaded into an Autodesk Revit 3D Building Information Model (BIM) (shown in Fig. 8). The BIM model was then manually updated based on on-site inspection, comparison to latest construction documents, and communication with the lead architect for the renovation project. The update included geometrical adjustments of individual components (where needed) and the definition of the components' materials (e.g., defining a section of a wall as a brick wall). Any components added during renovation were modeled in Revit based on actual dimensions and specifications as required for construction.

The next step included the use of the Tally LCA plugin [30] for

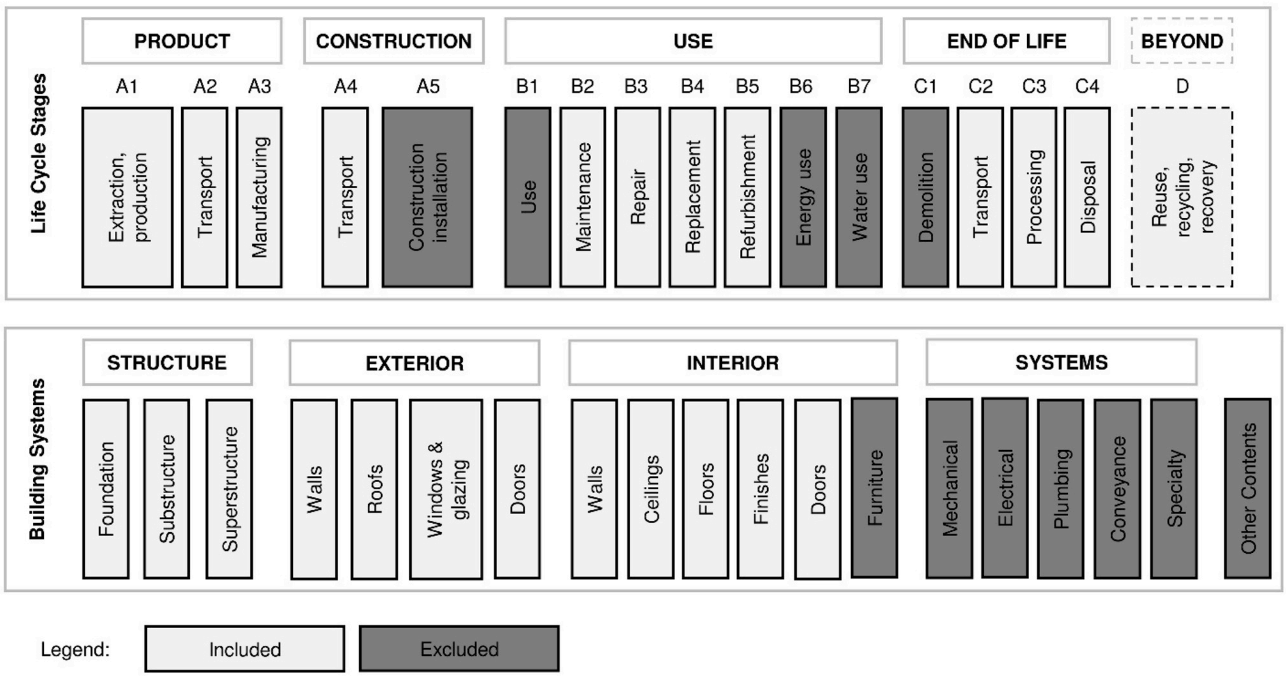

Fig. 7. Scope of assessment across life cycle stages and building systems.

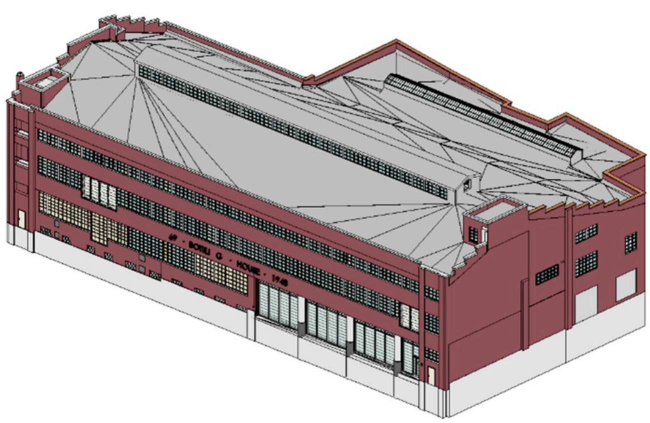

Fig. 8. BIM model of the case study building.

Autodesk Revit to assign LCA data to the components within the model. Tally is a BIM-integrated LCA tool which uses the BIM model's geometrical information about individual components together with its own database of material properties (e.g., material densities) and life cycle inventory (LCI) data to calculate the building's material quantities and life cycle impacts [31]. The LCI data within Tally is built on the GaBi LCI database [32]. It should be noted that some of the authors of this article have participated in the development of Tally.

The tool also contains a default database of service lives for each inventory item, which are used to calculate impacts due to material replacement. This study uses Tally's default service life data (provided in Appendix A), although it should be noted that there may be different replacement needs for reused components in the renovation scenario; something that was not considered in this study. For example, Tally assumes that structural steel frame lasts the full lifetime of the building (60 years in this study); however, the case study building's steel frame had already been in service for 65 years at the time of the renovation. There could potentially be a need for a structural retrofit sometime during the next 60 years. Considering service life within LCA is a difficult task especially relevant to renovations and should be further investigated in future studies.

The building model included all component types that Tally can assess; this includes ceilings, curtainwall panels and mullions, doors, floors, roofs, stairs, railings, structural columns and framing, walls, and windows. Electrical and mechanical equipment, controls, plumbing fixtures, fire detection and alarm system fixtures, elevators, conveying systems, furnishings, millwork, excavation and other site development are outside of the scope of this assessment.

The two scenarios considered in this study (renovation and new construction) required results from two separate Tally assessments corresponding to two different phases of the project:

1. Existing (i.e. original fabric and structure)
2. New (i.e. elements added during renovation)

The comparison of renovation to new construction was done according to the scope shown in Fig. 6 by selectively combining relevant stages for the new construction scenario and the renovation scenario. Environmental impacts associated with the new construction scenario were calculated by combining results from both the existing and new phases of the project and including all life cycle stages, as shown previously in Fig. 6b. Renovation impacts were calculated by combining all life cycle stages of the newly added components and the use stage of the reused components as previously shown in Fig. 6a.

3.3. Impact assessment method

The Tally LCA software calculates environmental impacts based on the TRACI 2.1 impact assessment method [33]. Although TRACI 2.1 normally includes both environmental and human health impact categories, this study focused only on environmental impact categories that can be assessed using Tally and are required for Leadership in Energy and Environmental Design (LEED) certification [18]. This includes the following 6 impact categories: acidification potential, eutrophication potential, global warming potential, ozone depletion potential, smog formation potential, and non-renewable energy demand.

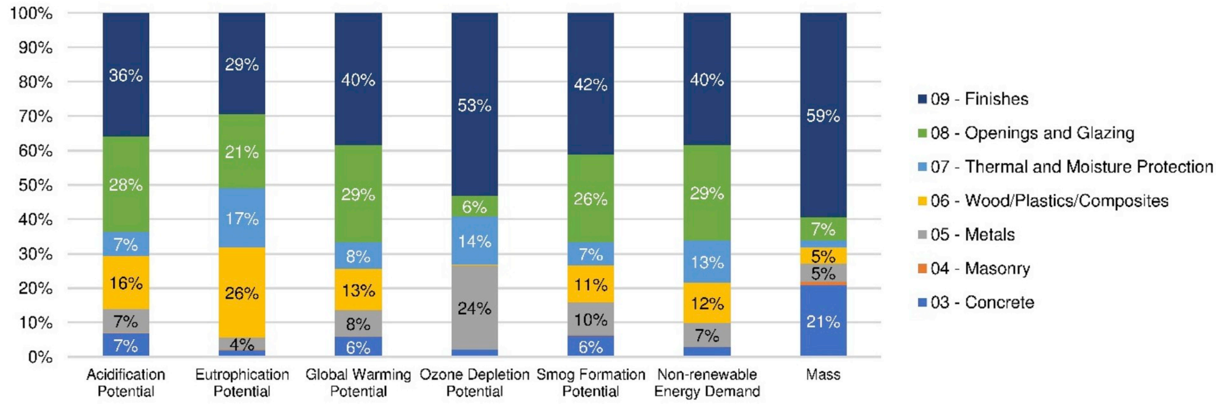

Fig. 9. Life cycle impact assessment renovation results by CSI Division.

4. Results & discussion

4.1. Renovation results

Fig. 9 shows the renovation results by Construction Specification Institute (CSI) Master Format Division. Finishes (59%) and Concrete (21%) produce the majority of the mass of components within the renovation scope. The Masonry Division is negligible in terms of mass and all impact categories as the only new components falling within this Division are small areas of added CMU and brick walls. The mass associated with other Divisions are fairly evenly distributed across the remaining 20%.

Finishes contributed to 29–53% of impacts across all categories and include components such as raised access floors, gypsum board, ceramic tiles, carpet, paint, and self-leveling concrete floor. Accounting for 20% of the global warming potential (GWP) of renovation, the raised access floors were the largest single contributor to impacts in this Division due to the steel and concrete in the floor panels. The impact of the panels is doubled because of the expected service life of 30 years, requiring full replacement at least once during the lifetime of the building. The expected service life was based on an Environmental Product Declaration for a similar raised access floor [34]; however, the actual service life could be substantially shorter or longer depending on the actual use and maintenance conditions. Carpet and paint were the next two largest contributors in this Division, accounting for about 6% and 5% of renovation GWP, respectively. These impacts are disproportionately large, when compared to the 2% contribution each of these components contributed to the mass of renovation materials. The painted areas included exposed structural elements which accounted for a third of the paint's global warming potential. It is important to note that the impact of the paint on structural steel is likely an overestimate given the use of a default 10-year replacement (repainting) cycle.

Since there was not much added concrete during the renovation, the impacts from the Concrete Division were minor. The largest impacts were seen in the acidification, GWP, and smog categories, accounting for about 6–7% of those impacts. The concrete was mostly added for floor infills, floor leveling, retaining wall repair, and new concrete sills and parapets.

Although the Wood/Plastics/Composites and Thermal and Moisture Protection Divisions account for only 7% of mass, the two Divisions combined contribute to over 14% and up to 49% of impacts across all impact categories. Components in the newly added roof and skylight are the primary contributors. The skylight panels (made of glass fiber reinforced plastic) and the EPS insulation are the two materials with highest impacts, especially in the eutrophication, global warming, and energy demand categories. The reasons for these components' disproportionate impacts are that they are both plastics made of fossil fuels, using energy intensive production processes, and that both are difficult to recycle (i.e. both are assumed as 100% landfilled at EOL in Tally).

Openings and Glazing account for 7% of mass but over 20% of impacts in all categories except for ozone depletion. The primary contributors in this Division are the aluminum frames (33% by mass) and glazing units (51% by mass) in the newly added windows. The aluminum frames are especially carbon and energy intensive, accounting for 67% of the Division's global warming potential impacts and 70% of the primary energy demand. Other components in this Division include door frames and hardware.

The Metals Division, like Concrete, accounts for a relatively small portion of the impacts across all categories. The only exception is the ozone depletion category where it accounts for 24% of the impacts; however, it should be noted that the absolute results in this category are small overall. Since there was minimal addition of structural elements during the renovation, most of these impacts come from steel studs in partition walls and stairs.

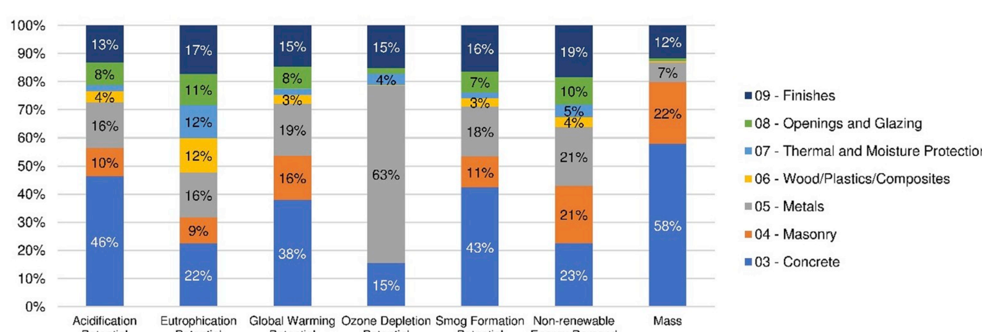

Fig. 10. Life cycle impact assessment new construction results by CSI Division.

4.2. New construction results

As shown in Fig. 10, the Concrete and Masonry Divisions account for the majority of mass in the new construction scenario (58% and 22% respectively), with Finishes accounting for 12%, Metals for 8%, and all other Divisions accounting for about 1% each. Concrete is also the major contributor to the acidification, global warming and smog formation potential categories, accounting for 46%, 38%, and 43% of those impacts respectively. In all other categories, Concrete accounts for 15–23%. The majority of the concrete is in the foundation walls, floor slabs, and encasing for steel columns and beams. All concrete within the existing components was assumed to contain no substitute cementitious materials (e.g. fly-ash), considering that the use of substitutes for cement was not common in the 1940's. Since the building is primarily supported with a steel structure, it is possible that much of the concrete and its cement content could be lower if current practices (e.g. concrete mixes with supplementary cementitious materials) were used for similar new construction project.

Metals' contribution of 63% to ozone depletion potential (ODP) is primarily due to the hot-rolled structural steel in the structural frame (77% of Metals' ODP); however, it is important to note again that the absolute results in this category are relatively small. Since the original building was designed to carry heavy machinery on each of its two main floors, the steel members may potentially be larger than what would be necessary for the construction of a modern office building. As such, the amount of hot-rolled structural steel would likely be lower in a new construction project for a commercial office use.

The masonry Division consists almost entirely of brick and mortar used in the building façade. For example, in the global warming potential (GWP) category brick accounts for 87% and mortar for 12% of the Division's impacts. The two major contributors to impacts from the finishes Division are terracotta brick (e.g. 61% in the Division's GWP) and gypsum wallboards (e.g. 9% in the Division's GWP).

4.3. Comparative results

The overall comparison of the new construction and renovation is shown in Fig. 11. In this case, renovation helped avoid between 53 and 75% of the impacts from the new construction scenario.

The largest reductions in environmental impact and building mass were in the Concrete, Masonry and Metals Divisions. These are Divisions with structural and envelope components that are typically manufacturing intensive but have long lifetimes and require relatively little maintenance.

The Wood/Plastics/Composites, Thermal and Moisture Protection, and Openings and Glazing Divisions saw little to no changes between new construction and renovation, as shown for the GWP category in Fig. 12. This is because many components falling within these Divisions had to be replaced during renovation or have shorter lifetimes, requiring some level of replacement during the extended life of the building. The most notable contributors in these Divisions are the newly added roof and windows.

The Finishes Division saw only a slight percentage reduction between the new construction and renovation scenarios. Components falling within this category are the interior terracotta wall tiles that were retained from the existing building (for new construction), and floor finishes, partition walls, ceilings, carpet, and paint added during renovation. Raised access floors added during the renovation were the largest single contributor to impacts in this Division, amounting to 20% of GWP of renovation and offsetting some of the benefits that would be associated with reuse of an existing floor.

4.4. Other considerations, challenges, and limitations

It is important to note that the original building was constructed for a different purpose and during a different time, likely resulting in different design requirements. It could be overestimating the impacts of a newly constructed office building using current trends and practices. On the other hand, the way the original building was constructed provided flexibility for its adaptive reuse and likely improved durability. If the building was originally designed as a lightweight building (i.e., designed to lower load carrying capacity), it may have not lasted much beyond its original design life and would have needed a major structural retrofit as part of the renovation. Other aspects of modern code compliance, such as more stringent minimum insulation requirements, could also change the impact profile of a modern office building in contrast to the historic building.

Ideally, the new construction scenario used for comparison with a renovation project would use a recent design of the same size and use type for comparison; however, it is typically challenging to create an alternative building design for the comparison due to the labor, time, and cost-intensive nature of design and modeling. For this purpose, it would be helpful to have a database of previously completed projects to use for comparison or a standard reference baseline building matching the use type.

5. Conclusion

Studies conducting LCA of building renovation projects typically face the issue of defining an appropriate study boundary and selecting the right scenarios for a comparative assessment. Defining the study boundary involves selecting life cycle modules to be included for the existing building and for the newly added building components. Comparative assessment scenarios may include the existing building in

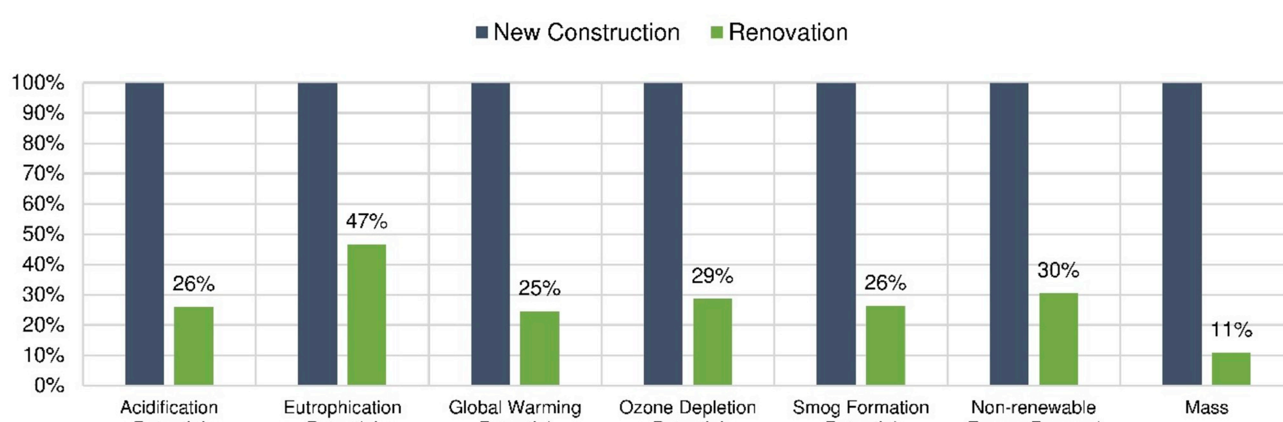

Fig. 11. Comparison of the total life cycle impacts of new construction and renovation.

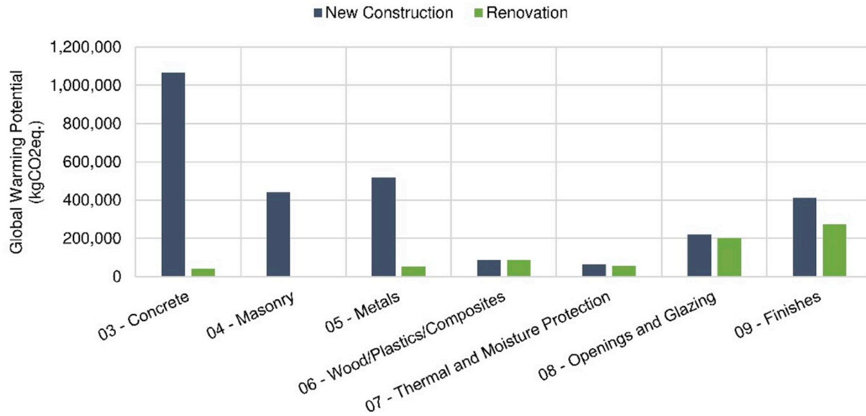

Fig. 12. Global warming potential by CSI Division for new construction and renovation.

its original condition, existing building with functional improvements (e.g. energy or structural retrofit measures), new construction substituting the existing building on the same site (where the existing building must be demolished), and new construction on an empty lot.

The EN 15978 standard defines refurbishment as a submodule of an existing building where the full life cycle of all newly added components is counted towards the refurbishment. Based on the standard and the building refurbishment boundary described in Vilches et al. [25], the use stage (module B) of the reused components from the existing building should also be included as impacts of renovation, as the prolonged life time of the building may result in additional use, maintenance, repair, and replacement of the retained components. However, the standard is unclear in its description of what elements of waste management should be included. Therefore, we recommended including modules A-C of newly added components together with module B of the reused components when calculating the impacts of renovation and comparing it to a new construction scenario.

The proposed approach was demonstrated on a case study of an adaptive reuse project. The renovation of the case study building was found to help reduce environmental impacts associated with the life cycle of building components by 53–75%. The most significant components added during renovation were the roof, access floors, and new windows, while the new construction scenario was overwhelmingly burdened by manufacturing intensive structural (concrete and steel) and envelope components (brick and terracotta walls). These findings are consistent with other studies finding structural and envelope systems to account for majority of embodied impacts of buildings [3,35]. The case study shows that these building elements may have longer effective lifespans than the typically assumed 50 or 60-year study period used for building LCAs, and their reuse can therefore greatly reduce the burdens associated with constructing new buildings. Another finding is that interior upgrades contributed to large percentages of the impacts associated with renovation. Some rating systems currently focus their LCA credits on structural and envelope systems and leave the assessment of interiors and finishes as an optional addition, which could lead to a missed opportunity to further promote impact reductions related to renovation projects. The case study also showed the strength of the proposed approach by allowing for direct comparison with a new construction scenario using a consistent boundary and scope.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2019.106218.

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