

Assessment of Materials Management Methods in Higher Education Building Lifecycle Decisions

SSM 4506W Capstone

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Executive Summary

Our team identified a need for sustainability considerations within the decision-making process for the end of lifespan of higher education buildings. This is primarily because they are too often demolished in favor of aesthetics and external factors rather than practical internal ones (Liu et al., 2014). As a result, these demolitions cause significant and unnecessary negative effects on both climate change and the environment (Coelho & de Brito, 2012). We developed a categorical assessment tool and research framework to analyze and compare additional materials management methods for higher education buildings other than demolition, with the goal of empowering decision makers to reduce organizational impact. This assessment was created for addressing multiple considerations for embodied carbon, material sustainability/disposal factors, and project financing in balance with one another and can easily be replicated by decision makers for their use in making real life decisions. To illustrate the effectiveness of our model, we analyzed a hypothetical scenario of either renovating or demolishing and rebuilding Green Hall, an academic building owned by the University of Minnesota. Using our model, we were able to show an over 2.1x increase in project embodied carbon, 1.9x increase in capital costs, and a 1.7x increase in total landfill waste as a result of enacting demolition and new building construction over renovation. Our tool also considered the weighing of different impact categories in terms of importance towards reaching 100% project goal fulfillment. By adjusting our needs to prioritize climate (50%), and environment (35%) over project financing (15%) our tool rated renovation (3.85/5) at almost double the effectiveness of demolition and new building (1.86/5). Once completed, this tool allowed for the decision makers we presented to at the MPCA quarterly Built Environment meeting to clearly see the associated impacts of different project materials management methods on climate change, the environment, and a decision maker's budget.

Introduction

Problem Statement

In higher education, large and ornate academic buildings are often built to last for a very long time. Due to this, issues often arise with building aesthetics, performance, and space usage in the long run, given how long they stay standing and the changing needs of academic institutions (Billelo, 1993). When stakeholders inevitably have to make decisions on how to mitigate these issues, we often see more concern for building appearance and department status rather than concern for reusing what is already there and enacting a more sustainable, reusable solution over building demolition. These decisions can see result in unnecessary demolition and its associated waste factors such as excess embodied carbon and landfilled material.

Currently, there is not an abundance of literature available regarding sustainability considerations in building material management methods. Especially in higher education where

we see these types of buildings, there are almost no resources available that illustrate the climate and environmental implications of these decisions to stakeholders and those with decision-making power over projects. This gap in between the academic resources on this topic highlights a need for a new type of framework to view these problems through a multifaceted, sustainability-focused lens. Given the nature of these decisions and the complexity of the issue, there is also a clear need for this type of framework to be adjustable to fit the needs of multiple scenarios, as well as consideration to practical and traditionally realistic factors in the process, such as the time and cost associated with building material management options.

Objective

The objective of this research is to develop a framework for analyzing various sustainability and feasibility considerations in higher education building management methods. This framework will allow decision makers to quantify the impact of their decisions in multiple categories relative to other available alternatives. In this discussion, we will primarily focus on demolition and renovation as materials management methods, but the scope of our framework will leave room for any number of other additional material management methods. Additionally, to model the usage of this framework in real time, a case study will be conducted on a relevant existing academic building within the University of Minnesota system.

Green Hall: A Case Study

Green Hall is an academic building located at the University of Minnesota Twin Cities, on the St. Paul campus. Through our calculations, we know that the size of the existing building is 49,785 gross square feet. The building was initially constructed in 1937 and has been renovated two times since it was built, in 1986 and 1988. The building's structure and architectural style is typical of the buildings constructed during the 1930s. This means that Green Hall was designed to hold heat, whereas modern buildings are designed and built to resist heat transfer with insulation (Fawaier et al, 2022). More specifically, Green Hall was constructed to have a high amount of thermal mass and not much insulation. The building is constructed largely of masonry (stone), brick, concrete, and steel reinforcements. In 1986, Green hall was remodeled to include a facade, pavilion, and a large laboratory. This involved the removal of surrounding trees as well as the addition of a large section of the building. In 1988, Green Hall went through another renovation where an elevator and a loading dock were added to the building. This renovation caused the removal and replacement of asphalt as well as an addition of the roof and increased overall material usage of the building. Green Hall is currently still in active use as an office building, research lab, and lecture hall, and its space is considered essential to the function of the college of forestry.

Based on its age and the current state of the building itself, Green Hall is a building we have identified as hypothetically requiring improvements and space reutilization within the next 10-15 years. Due to these factors, we will assume that building materials management methods will need to be assessed to address these issues in the near future, and as such have chosen to use Green Hall as a model in developing and demonstrating the usage of our analysis framework. This opportunity will serve both as an example for its usage in other projects as well as a discussion and justification regarding the nature of the tool and our methods.

Current State & Background

Current State

The renovation of buildings ranging from academic buildings to large commercial buildings can lead to several economic and social benefits. It can create jobs, stimulate local economies, and preserve the cultural and historical significance of a community. Renovating existing structures can also improve the energy efficiency and safety of buildings, as well as reduce operating costs and Greenhouse Gas (GHG) emission levels. Renovation can also increase the comfort of occupants through improved insulation and humidity levels. These benefits contribute to the overall well-being of communities and its residents (Ala-Kotila et al, 2020). We recognize that, on the other side of this topic, demolition of large commercial buildings can also provide economic and social benefits, including creating new job opportunities and opening up valuable land for redevelopment, which can stimulate local economies. Additionally, the demolition of unsafe or outdated structures can improve public safety and pave the way for the introduction of more innovative, sustainable buildings, using more sustainable building materials (C40 Cities Climate Leadership Group, n.d.). There are also several drawbacks to each that should be considered, especially those concerning costs to the environment and stakeholders.

If one wants to consider sustainability factors in choosing the right materials management method for a building owner or manager, such as demolition or renovation, there are several areas to look into. For example, we believe it's important to consider the embodied carbon costs associated with the implementation of materials management methods, which are the cause of the project's effect on climate change. These costs can change greatly based on the method used, and due to this variance it should be at the front of decision makers' minds when considering sustainability factors in building projects. The use of sustainable and environmentally-friendly building materials is also important in terms of environmental impact. Building projects using recycled or repurposed materials, along with newer innovative biocomposite materials, can reduce waste and limit the environmental impact of the project. Effective material management strategies, such as waste reduction, reuse, and recycling, can also help minimize the amount of waste generated during the project. Additionally, considering cost savings and project financing in conjunction with sustainability can greatly aid in making a project more attractive to decision

makers through cost savings or offsets from various sustainability programs. Our research explores all of these topics in order to paint the most holistic picture of the feasibility and impacts of a materials management method.

Background: Embodied Carbon

Embodied Carbon refers to the total amount of greenhouse gas emissions produced during the extraction, manufacturing, processing, transportation and eventual end of life stages for materials used in the production of a building (CLF, 2019). It accounts for a significant portion of a building's overall lifetime carbon footprint, and is compared in tandem with operational carbon - the greenhouse gasses emitted due to energy consumed in heating, cooling, and powering a building. Assessing a building's embodied carbon can provide insights into how a building's environmental impact could be reduced by revealing which structural materials are either outdated or outclassed by newer biocomposites (Real, 2017). It has been chosen as a factor for evaluation within this analysis because of the increasing awareness of GHG emission impacts in building projects. Conversely, demolition of existing buildings to make room for new buildings often lead to sending large amounts of building waste to the landfill, requiring new materials for the construction of the next building - both of which further increase the building's embodied carbon. Embodied carbon is important particularly in the context of University buildings because they are built to last, in contrast with commercial buildings that may be demolished due to changing market conditions or the need to keep up with modern technologies. However, decision-makers within the commercial building universe are increasingly aware that factors beyond cost need to be considered with an end-of-life building material management method. With a focus on sustainability throughout this process, embodied carbon is crucial for capturing a project's true impact on climate change, regardless of the type of building.

According to a 2019 report, building operations account for 28% of global carbon emissions, with an additional 11% stemming from the manufacturing of new construction materials (CLF, 2019). Typically, people only account for the energy usage and operational factors of a building, but this leaves a large hole in the picture. In order for a building to be fully evaluated for its carbon footprint, we must evaluate the embodied carbon emitted from the process of raw material extraction, transportation, and construction of the building, as well as the demolition of the building materials and disposal of these materials at the end of its life (Blay-Armah, 2022).

When a large building is renovated, the amount of materials needed to complete the project tends to be drastically less compared to those needed in constructing a new building. When renovating a building, the structural materials that contain the most embodied carbon are rarely touched. The American Institute of Architects even states that renovation projects typically save 50 to 75 percent of the total embodied carbon in comparison to building a new building (Strain, n.d.).

This statistic can be explained by the global warming potentials of the key structural components that go to landfill when a building is demolished. Each metric ton of concrete holds 0.6 metric tons of carbon dioxide (Fennell et al, 2021), with a metric ton of steel containing 2.8 metric tons of carbon dioxide (Purnell, 2013), and brick holding 0.2 metric tons of carbon dioxide per ton of brick (Quinteiro et al, 2014). Luckily, some materials such as brick and steel are able to be reused in a new building or are able to be adequately recycled for use in other building projects after demolishment.

Background: Material Sustainability and Disposal

Various materials management methods for buildings require significantly different amounts of new material, and produce substantially different amounts of material waste. Therefore, material usage is an important factor to consider due to the high environmental impact that material waste and disposal have on the environment, as well as the financial cost of required new materials and material waste. Material usage also carries social significance in the ways that it can improve comfort and safety for occupants (U.S. Department of Energy, 2009). The environmental, social and financial costs and benefits vary greatly for both the renovation and demolition options for commercial buildings.

If a building is deemed viable for renovation, the process, materials, benefits, and costs of renovation can further be explored. With renovation, the potential lifespan of the materials in the building that already exists are being further utilized instead of being unnecessarily disposed of, in which new materials would be extracted, crafted, transported, and constructed in their place. With that, logically, renovations entail significantly less material waste than demolition. This is because most of the structural aspects and materials that are already present are largely conserved. Specifically, this includes the concrete structure, floor slabs, and exterior walls. Other structural aspects, such as staircases and elevators, are often left in their original locations as well, due to the difficulty of relocating such structures. The environmental benefits of renovation as opposed to demolition for new construction appear to be widely accepted in the construction industry. According to a report produced by the National Trust for Historic Preservation, “when comparing buildings of equivalent size and function, building reuse almost always offers environmental savings over demolition and new construction” (PLF, 2016).

There are also various potential drawbacks that accompany the renovation process. As a building viable for renovation is often not considered “state of the art”, the age of the existing building, the state of the materials in the building, as well as the projected potential lifespan of the building must also be considered. The state of the original materials within the building can affect the extent to which the building should be renovated and when further renovations or maintenance would be required. This is important to consider in the scenario with Green Hall, particularly due to the fact that it was originally constructed in 1937, with the most recent renovation being

completed in 1988. A renovated building is typically not considered “state of the art”, and often does not have the same aesthetic appeal that a “state of the art” building would.

There are some aspects that must also be considered in the renovation planning process. First, when considering renovating a building, it is important to understand the structural standards of the time period in which the building was constructed, and what that entails for any renovation. For example, buildings in the past were designed to hold heat without a lot of added insulation, whereas modern buildings rely on insulation to act as a gasket to diminish heat transfer (P. Hilger, personal communication, March 15, 2023). For this reason, many renovations begin with the primary goal of adding, replacing or improving insulation. This provokes the question of how the building can be renovated to most effectively utilize the present structure and materials in order to reduce resource consumption, environmental impact, and costs, while also increasing not only the efficiency, but also the sustainability of the renovation process and the end result.

The single-most important metric to consider when discussing material usage in demolition is the amount of waste generated in weight. According to the EPA, “600 million tons of Construction and Demolition (C&D) debris were generated in the United States in 2018, which is more than twice the amount of generated municipal solid waste.” The EPA’s Fact Sheet also states that demolition accounted for 90% of the C&D debris, with construction accounting for the remaining 10% (EPA, 2018). Without a way to reuse demolished materials, landfills become inundated quicker and eventually new landfills will need to be created, which is a tough sell when no one wants to live near a landfill. This creates the need for innovative building materials that contain components that can be broken down and reused or recycled, as well as constructing building materials that generally last longer and are more durable.

There are several circumstances in which demolition of a building might make sense from a materials standpoint. The first is when the general function of the building is being changed. For example, there are many offices that are now vacated due to work conditions changing after the events surrounding the COVID-19 coronavirus pandemic. Due to greater numbers of people working from home, there have been suggestions to change the function of these office spaces into apartments or other types of housing, which raises the question of feasibility surrounding the changes that would have to be made (Campion et al, 2022). The popular option would be to renovate such buildings. But moving staircases and elevators around can be very costly and time consuming and are thus commonly avoided during the renovation process (Sandbulte, 2023). The new housing may require more window space, updated plumbing, and other structural changes that completely change the function from before.

A building may also require demolition because of either perceived or actual structural or safety issues. Many older buildings were built during a period when standards were much less stringent than today’s standards, considering both environmental regulations and building performance

protocol. Updating the building to current standards may lead to decision-makers to feel that demolition of a building is most cost-effective (C40 Cities Climate Leadership Group, n.d.). A building may also contain asbestos or lead, in which case it may be viewed to be safer to demolish rather than remove the hazardous material(s). One study suggests that “the case for demolition is based on the argument that this is essential to reach a 60% cut in total energy use in housing by 2050” (Power, 2008). We know that this outcome can be achieved with renovating buildings AND building new, energy-efficient buildings.

When determining the materials that can be used in the construction of new commercial buildings, it's important to understand which attributes are most important to the success of the building's life. Concerning its environmental footprint, the material should have a minimal impact on the environment during each phase; this includes the extraction, production, transportation, installation, operation and disposal phases that encompass cradle-to-grave analysis. The material also needs to be durable and long lasting, without the need for frequent maintenance or replacement. To counter the issue of material waste, a sustainable material should be either recyclable or reusable to some degree. Products like brick can be processed post-demolition and turned into crushed brick. “The mechanical properties of crushed brick have been found to be comparable to conventional quarry materials in various civil engineering construction applications” (Arulrajah et. al, 2017). Material in a new building will also have to be readily-available for large scale use, both in sourcing and generation. Sustainable materials may improve the energy efficiency through improved insulation or reduced heat gain, and may be cost-effective and competitive with traditional building materials. The material used in new construction should lastly be low in volatile organic compounds (VOC) and other harmful substances.

A challenge in implementing newer, innovative materials that may be more sustainable is the fact that they haven't been readily-tested, and therefore building planners lack the confidence needed to implement these materials into the construction of new buildings. People in charge of designing campus buildings are planning on the building lasting for a very long time, whereas people building commercial buildings may be looking at a much shorter window to receive their payback value. With this in mind, commercial buildings are much more commonly used as a way to introduce new and promising materials.

Background: Project Financing

There are several unique factors to consider in financing a sustainable building project especially when considering the varying nature of the project type itself. Oftentimes, consideration for project financing in higher education focuses primarily on the initial capital cost and project timeline. This is due to the fact that the project can be dependent on funding available at the time and that the construction of a building will not necessarily bring in new profit for a university.

However, the focus on sustainability necessitates the consideration of many additional factors which may not have initially been considered relevant to the decision (Shan et al., 2017). By informing a decision using both standard considerations and incorporating new innovative ones, stakeholders can reach a decision that is more equitable for planetary health while accomplishing their facility needs.

Capital costs are the upfront costs associated with completing the proposed project. They are typically determined by undergoing a discovery phase involving multiple contractors who would utilize information available to them to estimate the process and costs associated with the project (Caffieri et al., 2017). They would then create an estimate including labor and profit margin on their end which would be submitted as a bid to the university. Using these bids, the ideal contractor candidate would be chosen and the university would proceed with the project. However, it almost never goes this smoothly, because while the project is carried out, unseen complications arise which end up increasing capital costs. Oftentimes we see these costs being far higher within new building projects, as there are additional costs associated in the process and more materials are needed overall to produce the end product (Morelli et al., 2014). Additionally there are higher up front costs for building design, permitting and additional technical requirements such as hooking up water and electricity to the building.

Another factor that should be considered within the initial costs is the time investment associated with the selected project. Based on the nature of the project, the duration of construction processes until completion could vary from anywhere between 6 months to multiple years. In general, it can be said that the renovation process takes far less time than a comparative demolition of an existing building and construction of a new building, usually about half as long depending on project circumstances and size (Hale et al., 2009). This is not only because demolition and construction of a new building involves more steps in the process, but also because a new building runs into more hurdles like site surveying, permitting, and materials sourcing.

In enacting a building materials management method that makes a more efficient building, there is an opportunity to assess return on investment (ROI). This would be a true financial return on investment through a cost savings perspective. In higher education, the investment into a new building project will not necessarily yield a direct return through the form of profit from the reutilized space, but it could yield returns in the form of cost savings through reduced operational costs. By improving a building's insulation, heating & cooling system, and retro-commissioning or retrofitting electrical equipment, the operational costs of a building can be significantly reduced (Dobiáš & Macek, 2014). Over time, the summation of these savings in operational costs can partially or in some cases fully offset the initial investment cost of the project. The other way to look at hidden costs or benefits through a sustainability lens is by including the carbon emissions savings of the project as a financial savings factor. By utilizing the EPA's

model for the social cost of a ton of carbon dioxide emissions, one can further use estimates for the total embodied carbon of various project options as cost factor as well. This is defined as the detrimental health impacts to residents of the world from adverse health effects associated with climate change and GHG emissions (EPA, 2023). The difference in embodied carbon of the various facility project options can be accounted for as a monetary decrease in benefits for a project over time and can give stakeholders a truer understanding of the financial costs associated with their project.

Additional financing options can also dictate the feasibility and ease of implementation of a building project. There are many available options for a project seeking to incorporate sustainability into its frameworks such as grants, material cost savings, co-benefits from project design, and availability of rebates post-completion (EPA, 2016). Before undertaking a project, these options should all be explored as they may help to offset capital costs as well as provide some measure of additional value to the project depending on the circumstances. Many grants related to sustainable building practices have recently become available through the Inflation Reduction Act of 2022 as well as state level opportunities which have become more prevalent in recent years. The state level opportunities are typically more geared towards upgrades to building operating systems and specific project installations while federal opportunities are more all inclusive as large package amounts for retrofits, making them ideal for renovation and the former ideal for new systems in a new construction building. Additionally, one typically sees an increase in rebate rates on average when they upgrade or construct a replacement building, although they are typically greater in renovation over demolition (USGBC, 2023).

Methodology

Approach

Our team has identified three impact categories discussed below which will be the primary factors in determining the eligibility of both materials management methods in meeting project goals. Of these categories, several subcategories can be directly identified which all can be associated with numerical or qualitative values. These subcategories (such as materials landfilled or materials recycled under the main impact category “Material Sustainability and Disposal”) will all be evaluated for each option and ranked in comparison to one another. These subvalues found through our research will then be input into the scoring matrix outlined later in this section, which can be used to analyze all relevant factors together and aid in making a decision. The exact method for calculation of these subcategories is defined below.

Framework Concept

While the findings of this research will be written within the context of examining Green Hall as a case study, its primary goal is to be used as a framework for promoting sustainable decisions in similar buildings. In reading this assessment, stakeholders for decision makers should consider the processes undertaken in relation to the building being analyzed, attempt to replicate them and draw conclusions for their own projects, and make due adjustments where needed. Especially in terms of the research done into the various subcategories outlined, many of the solutions discovered in this writing have a broad range of applications, and it is likely that some form of many of them would be available for use in most circumstances (for higher education specifically). The methods for categorical analysis, scoring options, and relevant tactics described in this paper should be used to best inform decision makers on the impact of their options.

Feasibility

In order to apply our system for incorporating sustainability factors into the decision making process in a buildings lifecycle planning, it is important to first establish whether or not the luxury of these various options can be afforded. Oftentimes there are specific circumstances in which a building must be torn down or at least partly demolished. These circumstances can include many variables:

- Failure to meet current regulations or safety standards in its current state
- Hazardous site factors preventing safe facility site repurposing
- High moisture presence within insulation materials

These pertinent factors need to be considered by stakeholders before an analysis is conducted on sustainable building options in order to establish what is feasible for a project.

Assumptions

For the purposes of our hypotheticals, we will assume a few conditions for our estimates, both in order to address our time constraints within this project and more realistically address the needs of stakeholders in this issue:

- We will assume that under both renovation and demolition/new construction that each final building state will have achieved the LEED Gold standard upon its completion, as this standard fulfills the requirement of creating a more sustainable building and allows us breadth to make recommendations based on this goal (*LEED Rating System* | U.S. Green Building Council, n.d.).

- We will assume a final product square footage increase of 15% both within building renovation (which will now be referred to as renovation/expansion) and new construction. This is because the needs of a building project typically include demand for more space utilization (Liu et al., 2014).

Materials Management Methods

The specific outline of the materials management methods for the hypothetical Green Hall project are listed below. Note that the usage of this framework in analysis does not exclude the consideration of any other method such as deconstruction or partial demolition.

- **Demolition and Construction of a new building:** Green Hall, as it currently stands, will be completely demolished, and in its place a brand new building will be constructed with a 15% increase to square footage. It will also be constructed to meet LEED Gold standards.
- **Renovation and expansion of the existing building:** Green Hall will see very minimal demolition practices and its interior will be updated to achieve a new look. It will also see an expansion to its front equivalent to 15% of the existing square footage. It will also be renovated to LEED Gold standards.

Impact Categories and Subcategories

In our framework for analysis, we will observe three project impact categories in order to paint a more holistic picture of the issue. These main impact categories are broadly defined for the scope of any relevant project. Subcategories listed below them are more specific so they can be defined through research. Stakeholders should research all of these focus areas in terms of

- **Embodied Carbon:** Considering embodied carbon in the total lifespan of the building project, from the existing structure to whatever replacement materializes at the end of the project. This helps us understand the project's effect on climate change.
 - Total Embodied Carbon - The total quantity of embodied carbon emissions associated with completing a building materials management project, the sum of which is found from the embodied carbon of existing materials destroyed as well as new materials used in the building
- **Material Sustainability and Disposal:** Assessment of options for utilization of sustainable materials within project execution. Exploring how these materials can offset

waste or environmental hazards and provide additional benefits. Also, the assessment of the total mass of materials going to the landfill associated with the completion of the project as well as amounts recycled

- Reusability of materials - Assessing which existing materials within the existing building could be reused or recycled. Exploring the opportunities available for reusing them or purchasing third party recycled materials in the new project.
 - Feasibility of sustainable material usage - Assessing whether the cost, market availability, and location of sustainable replacement materials allow for them to be used in either management option. Additionally, considering whether there are other opportunities to use sustainable materials which are non primary to our analysis (i.e. not steel, concrete or brick) where they were not used before.
 - Opportunities for co benefits - of the opportunities for sustainable or recycled material use identified for the project options, do they provide any additional benefits to stakeholders (i.e. increased insulation, stronger structural value, reduced hazard, etc).
 - Estimated waste volumes - Determining the total amount of waste material generated and sent to the landfill by fulfillment of either project option, estimated using obtained building knowledge. This can also be offset by recycling volumes and analyzed as a percentage of total project mass.
- **Project Financing:** Securing proper funding to take on a project is critical in actually seeing a concept all the way through in its goals. Exploring green financing options can promote the adoption of more sustainable practices and attract interest from investors committed to these issues.
 - Return on investment (ROI) - Finding the savings in return of the project generated by operational efficiency and added value from the end result of the project options (from being LEED gold). Calculated by estimating savings from energy and natural gas efficiency. Also considering the negative return of the social costs of carbon estimated using embodied carbon, found by multiplying the EPA's standard value by the embodied total carbon mass for each option.
 - Capital costs - Determining the upfront costs of completing each building material management method from start to finish, found by summing materials and labor cost estimates, permitting and architectural fees, demolition costs as well as considerations for duration of project completion.

- Available alternative funding options - Assessing the various funding source availability from both the federal and state governments through recent initiatives at the respective site. Considering how these options differ based on the nature of the material management method being used. Also considering average increase in rebate amounts from completing either project option.

Embodied Carbon Methods

Given our limitations with the availability of data and time constraints, we will be primarily accounting for the embodied carbon of the envelope structure of Green Hall itself, and not every single material incorporated into its design. Our focus will be limited to the main skeleton and supporting elements of the building such as the exterior walls, floors, support mechanisms and roof, which are referred to as building envelope structures. We are confident with this scope, considering the fact that the structural components of a building account for 55% of a newly constructed building's embodied carbon (Pearson, 2020). Because it encompasses the majority of embodied carbon and we are simply using estimates for this number to compare two options and finally rank them in comparison, accounting for 100% of embodied carbon is not crucial to the end goal for the sake of this assessment. The materials included within our defined structural scope, within the envelope of the building, are concrete, steel, and brick. Materials such as drywall, tile flooring, windows etc are excluded from our analysis of embodied carbon.

In order to calculate the embodied carbon of Green Hall as it exists and in hypothetical future states of new building or renovation, our team utilized the Kaleidoscope embodied carbon building LCA tool (<https://www.payette.com/kaleidoscope/>) to calculate embodied carbon from the materials that we have information on using standardized variables provided through research. This tool includes calculations for the carbon factors from extraction, processing, production, transportation, and landfilling of building materials. To pursue the most accurate estimation of these material amounts, we secured and analyzed design and engineering documents, both in initial construction and its previous expansions, which outline the structural materials used within Green Hall as it currently exists (Johnston, 1937). For materials not as established in the building sector, we utilized peer reviewed articles to gain the best assessment of the carbon emissions related to the production and use of these materials.

Definitions:

- **Embodied carbon:** defined as the amount of kg CO₂eq equivalent of all types of greenhouse gasses associated with impacts within our scope.
- **Carbon footprint:** refers to the greenhouse gas emissions associated with a material - including both operational and embodied emissions.

- **Life cycle assessment (LCA):** a methodology used to quantify the environmental impact of a material over its entire life cycle, from extraction of the raw materials to its disposal and end of life.
- **Global Warming Potential (GWP):** a measure of the impact that greenhouse gasses such as CO₂ have on the environment over a given period of time.
- **Kg CO₂eq:** the common metric for estimating kilograms of carbon dioxide equivalent greenhouse gas emissions.
- **Building envelope:** includes all structures which solely separate the interior from the exterior of the building.

In our first scenario consisting of the decision to demolish Green Hall at the end of its life and create a new replacement structure, we assume that the new structure would be of equal square footage. This structure would use a similar amount of construction materials, however the nature of these materials could be changed to feasible alternative options (See Material Usage Section). Based on these assumptions, we created an estimation for material types and usage which was also analyzed through the Kaleidoscope tool to determine the amount of embodied carbon that would be added to the existing amount from the previous structure.

For the second scenario of renovating and expanding upon an existing building, we assumed an expansion of 15% square footage while also utilizing more sustainable materials. We also assumed a scenario in which there is no expansion of building square footage, but there is a removal and installation of a new front-facing building facade. The additional embodied carbon estimates from these scenarios will be added to that of the existing Green Hall calculations.

Following the steps described above would likely yield sufficient results in other cases, however based on individual circumstances, the process should be analyzed to see if adjustments would be made in different cases. For instance, not every project would be assuming the same structural makeup or assumptions on final building size. However, the methodology and tools suggested should prove useful in calculating these factors for most other buildings. Stakeholders should consider this in following our model for research and analysis.

Material Sustainability and Disposal Methods

Regarding the usage of sustainable materials, recommendations will again revolve around the structural material of the building's envelope, which includes brick, steel, and concrete. Materials that make up the inside of the building will also be considered, but to a lesser degree. Various alternative or reuse options for our primary researched materials brick, concrete, and steel will be evaluated qualitatively regarding cost, market availability, and location which will aid in choosing when and where they could be used in our various options.

The ideal recommendations provided for each materials management option will be used as the basis for a hypothetical project plan, both of which can then be evaluated against one another. Using these findings, the offsets to landfill and recycling factors from the materials assessed will be evaluated in a materials balance calculation in order to determine the amount of net waste going to the landfill from each option. The same assumptions as taken above for the building process and final square footage of the building in each option will be used in this case for consistency and to create a hypothetical new material makeup. Finally, the opportunities for co benefits and additional sustainability factors from a materials standpoint will be assessed based on the nature of each project and the newest cutting edge technologies available. This is another category which cannot be comprehensively qualitatively analyzed but best practice judgment will be used to reach conclusions within this category.

Stakeholders or those with power over these projects should seek to research what materials or processes in building materials management methods would be most meaningful and beneficial to their individual circumstances. Due diligence should be done in understanding the current state of research materials and new findings as progress is made in these areas to most holistically consider all aspects discussed in this writing for each scenario.

Project Financing Methods

Our primary considerations for project financing will include capital costs, ROI, and availability of alternative financing options. In considering project financing through the subcategories we've identified, we will define the boundary of financing for a project as only costs associated with these metrics which directly pertain to the future lifespan of the existing building or new project. Our team will conduct extensive research on the financial metrics outlined and provide reasonably estimated figures on what costs or savings could be incurred for the two materials management methods being used on Green Hall.

Capital costs will be estimated using average contract bid estimates for education facilities by square foot as well as relevant necessary values from existing literature. ROI will be calculated from direct savings from operational cost improvements from meeting new energy efficiency standards (LEED Gold). Social Costs of Carbon will also be considered based on the EPA's current model using an average 3% discount rate. The opportunities for alternative project financing options will be quantitatively analyzed based upon what options would be applicable and available for utilization in Green Hall specifically. We will research what funding could realistically be considered for projects of this type of University building. These metrics will be considered in ranking our building management options against one another and all categories will be considered in producing a final score for the project financing category.

Decision makers replicating our model could use the methods described above in their circumstances but they ought to exercise care in researching what factors might best apply to them. For example, they would research what average Energy Use Intensity (EUI) and \$/kWh would best apply to their local project. We recommend that stakeholders pursue findings in the same categories that we've explored, although they should not necessarily follow our estimates exactly, as there are a variety of specific factors that should be considered in each unique building project.

Scoring Matrix Method

In order to effectively weigh and categorize all aspects of our materials management method options at once, our team developed a request for proposal (RFP) style scoring matrix to rank individual subcategories of our three impact categories (Figures 1, 2). The main impact criteria in bold on the left are numbered 1-3, and each has a number of subcategories beneath it which we will evaluate as discussed above. There are two columns (one for each management option) vertically where a rank of 1-5 can be given to each subcategory based on our findings. The average score for each main criteria per each management option will then be found by taking an average of all subcategory scores in that impact category. This then ranks the overarching impact category ranking for each option against one another. Additionally, this system allows us to give a "weight" to each impact category to encompass a more comprehensive and nuanced approach given the specific site needs at Green Hall, as seen at the bottom of the scorecard. Our weights will be determined through our research and conversations with various stakeholders in order to attain an unbiased and fair ranking of importance in these decisions. The average scores for each criteria are then multiplied by this weight and summed up in order to statistically incorporate the importance of each impact category into the composition of the final score for each method. This final number which is depicted will be the final basis for our recommendation on Green Hall. Additionally, this scorecard is replicable for usage by decision makers and can be completely adjusted to include different subcategories, impact weights and materials management methods. The intent of this is to allow it to be used in various circumstances which are different from Green Hall but in which the value of embodied carbon, material sustainability/disposal, and project finance are all still prioritized and need to be considered in balance with one another.

Embodied Carbon

Existing Structure

When calculating the embodied carbon figures for Green Hall's current state, we had to use a multitude of sources of information and tools. Firstly, we were given blueprints for the original construction of Green Hall from 1937 (Figure 3). We used these blueprints to calculate the material makeup for the three main materials used in the structure of the building, which holds

the greatest amount of embodied carbon. These three materials are brick, steel, and concrete. We first calculated the volume in cubic yards of concrete based on the joists, beams, and floor slabs in the building. We then calculated the mass in tons of steel based on the amount of rebar used. Lastly, we calculated the square footage of the exterior of the building and subtracted the square footage of the windows to assess the amount of brick used.

In order to navigate these blueprints, we were able to meet with Peter Hilger, the faculty director in the construction management program, to receive multiple lessons in architectural engineering. Next, knowing the amount of materials that were used, we could then use both the Kaleidoscope tool along with GWP figures from peer reviewed articles to convert our findings into metric tons of carbon dioxide equivalent emissions.

Section	Volumes (Metric Tons)				
Category	Total concrete used in lifecycle	Total brick used in lifecycle	Total steel used in lifecycle	Ferrock used in lifecycle	Total
Existing Structure	1972.4	503.9	25.7	0.0	2502.0
Renovation	1972.4	579.5	29.5	295.9	2877.3
Demolition / New Building	4240.6	1083.5	55.2	0.0	5379.3

Table 1: Green Hall Material Mass Balance Estimates

Through our calculations of the current structural materials in Green Hall as it stands today, we have been able to account for the following amount of material used: 1972.4 metric tons concrete, 503.9 metric tons brick, and 25.7 metric tons of steel (Table 1). When analyzed using global warming potentials of the key structural components from existing peer reviewed literature, we found an estimated 1307.5 metric tons of CO₂eq in the existing structure (Table 2). Through this analysis, we see that Green Hall used a relatively large amount of concrete, which should be considered in a future building redesign and/or demolition & new construction of a building because of its high material impact.

Section	Emissions (Metric Tons CO2e)				
Category	Concrete	Brick	Steel	Ferrock	Total
Existing Structure	1226.8	80.6	71.9	0.0	1307.5
Renovation	1226.8	92.7	82.7	-14.8	1319.6
Demolition / New Building	2637.7	173.4	154.7	0.0	2811.0

Table 2: Green Hall Embodied Carbon Estimates

The total embodied carbon of Green Hall would be much higher if we were to add into account the embodied carbon of additional materials, such as flooring, walls, doors, windows. It would also be different if the specific transportation and installation data were present specific to Green Hall's location and the location in which the building materials were manufactured. Due to the information that was included in our architectural documents of Green Hall, as well as the notion that the structural materials hold the bulk of the embodied carbon of a building, we can still be confident that this metric shows a fair estimation of the embodied carbon in this building.

Errors in calculating the embodied carbon in a building fall often occur because of the lack of available data on the life cycle of various building materials. In order to successfully quantitate the global warming potential of a ton of material, one must know how the material was transported to the site, the energy it took to put this material into the building properly, the amount of waste that is created, and where this waste ends up. This makes it hard to establish calculations from a research standpoint, as the data collected is only as good as the sources and tools containing the information will allow.

Renovation

Extrapolating from the metrics of the current materials that are used in Green Hall and adding the 15% expansion, the option of renovation would use 1972.4 metric tons of concrete, 579.5 metric tons of brick, 29.5 metric tons of steel, and 295.9 metric tons of Ferrock, according to our projections and methods (Table 1). Through our calculations of the embodied carbon in the current structure of Green Hall, including a 15% expansion, we have been able to account for the following embodied carbon figures outlined in Table 2, showing a total of 1319.6 metric tons CO2e for the renovation option. For the 15% expansion to Green Hall we decided to use the

material Ferrock in place of the additional concrete, which actually provided a negative value to CO₂e emissions due to its properties. The reason for this will be discussed in the materials section. Because of this, even with the 15% expansion of Green Hall, only 12 metric tons of CO₂e were added when compared to the embodied carbon of the original building.

We estimated that the 15% square footage expansion could be attributed to a green roof expansion, larger entryway facade, auditorium expansion, or new laboratory space, among a plethora of other options considered by the stakeholders. The expansion was standardized and framed as an extrapolation of simple raw material usage to facilitate the option for the stakeholders to choose; however it should be noted that differences in material use between choices would dictate the true increase in embodied carbon.

Demolition and New Construction

Taking into account our calculations for the amount of materials that are used in the current structure of Green Hall, we can extrapolate these figures to project that the option of demolishing Green Hall and creating a new building would use 4240.6 metric tons of concrete, 1083.5 metric tons of brick, and 55.2 metric tons of steel (Table 1). For reasons discussed in the next section, Ferrock was not included in this projection. Using these numbers we were again able to project the total project lifetime's embodied carbon using the Kaleidoscope tool which gave us the numbers seen in Table 2. For the demolition and new construction materials management method, we estimated a final total of 2811.0 metric tons CO₂e. This is more than double the existing embodied carbon within the Green Hall building currently.

For the embodied carbon of the new construction, we have assumed that the concrete, steel, and brick all came from the same manufacturer as the current structure. We also assume that the building practices regarding installation of these materials stayed the same as the standards that were followed when the original building was built in 1937. Additionally, although recycled brick could easily be used as we will discuss later, this brick would still contain the same embodied carbon as virgin brick material would. These assumptions must be made due to our team's available timeline to complete this project as well as the current lack of relevant literature pertaining to this specific factor in higher education facilities.

Material Sustainability and Disposal

Sustainable Material Options

When considering options for materials in both the renovation and demolition for new construction options, materials that were researched fell into one of two categories: 1. reused materials or 2. sustainable alternatives to industry standard materials. Each of these options were

analyzed with a set of criteria to evaluate the feasibility of using them for this specific project, including market availability, overall cost of the material, as well as location of the project. After exploring many options, the best materials for Green Hall were narrowed down to Ferrock being used in place of concrete and recycled bricks.

Ferrock is a compound that has been found to be a phenomenal substitute in concrete; it is known to be five times stronger than concrete, requires a lower maintenance cost due to the increased strength, is lighter in weight than concrete, and is considered to be carbon negative. The aspect of Ferrock that makes it both carbon negative and significantly stronger than cement is the manner in which it is formed, or dried, in that the absorption of carbon dioxide reacts with the iron to form iron carbonate, which can easily adhere to the substrate (Niveditha, 2020). Given the extremely high GWP of concrete, as mentioned earlier, makes Ferrock a much more environmentally friendly option (expand and add in sources). Regarding composition, Ferrock is composed mainly of recycled materials, generally being 60% iron dust, 20% fly ash, 12% metakaolin, and 8% limestone (Vijayan et al, 2020).

Regarding the aforementioned feasibility criteria, Ferrock easily meets the criteria for location of the project and market availability. Ferrock is commercially available in Minnesota and it is also functional in all aspects of Minnesota's varying climate due to the fact that Ferrock is a very versatile building material. Regarding the cost feasibility factor, the pricing of Ferrock varies by location, but it is generally a higher up front cost than regular concrete, which could change in the near future (Garcia et al, 2017). The benefits of investing in this material must also be considered due to all of the benefits that accompany the use of Ferrock.

A potential drawback to consider is that although Ferrock is such a sustainable option, it does rely on waste of other resources. Therefore, theoretically, if Ferrock becomes an extremely popular structural material in the future, it is possible that it may not maintain its impressive sustainability factor due to the requirement of the waste of other resources as an ingredient. This is not considered an issue for the purpose of this project or any project in the near future, due to the fact that Ferrock has not yet become a dominating material in the construction industry, and waste materials are sadly seemingly endlessly available. Regardless of these drawbacks, the use of Ferrock is still much a much more sustainable building material than cement.

Recycling building materials has been proven to be overall more sustainable than replacing existing buildings with brand new buildings, using brand new materials, "expending significant new energy and carbon now to replace existing buildings with new construction is potentially counter-productive to our most pressing carbon reduction goals, particularly if the carbon 'break-even' point is 35-70 years in the future. The initial bursts of new carbon into the atmosphere will have an immediate detrimental impact, at a time when society is struggling to stabilize and reduce our greenhouse gas emissions" (Adlerstein, 2016). With that, recycled bricks have been

found to be more sustainable than using brand new bricks. Research has shown that bricks can be reused if they meet certain strength criteria. Recycled bricks would likely be purchased from a third party company that specializes in brick reuse rather than reusing the existing bricks from the building, and those bricks from the site would be sent to the third party company for recycling (Juve, 2023). This outcome is because there are certain specifications for bricks that are used on the interior or exterior of a building, an interior brick cannot be used on the exterior (Juve, 2023). Recycling bricks significantly extends the lifetime of the material, sends less mass to landfills, and requires minimal new material, and can be used in/for....

Material Disposal

Our team analyzed metrics of the waste volumes that each option would entail. Using the existing structure, as is, as a baseline, the volumes in tons of materials displaced for each option considered are shown in Table 3. The table displays amounts being wasted or recycled for each material, as well as volume totals, being total landfilled mass, total recycled mass, and finally net waste to landfills and net waste as a percentage of the total project mass. In Table 3, it can be seen that a renovation and expansion would entail 216.4 metric tons of net material waste to landfill, which means that 7.5% of the total project mass would be sent to landfills. It is also shown that the option of demolition of the existing building and construction of a new building would entail 1,442.8 metric tons of net material waste to landfill, or 26.8% of the total project mass, to be sent to landfills. We are aware that there is a possibility for inaccuracies in the data due to potential errors in overall material waste stream calculations.

Section	Material Waste Management (Metric Tons)						
Category	Steel Recycled	Brick Recycled	Concrete Landfilled	Total Landfilled Mass	Total Recycled Mass	Net Waste to Landfill	(Net % to Landfill/Total Project Mass)
Existing Structure	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Renovation	3.9	75.6	295.9	295.9	79.4	216.4	7.5
Demolition / New Building	25.7	503.9	1972.4	1972.4	529.6	1442.8	26.8

Table 3: Material Waste Balance Estimates for Green Hall

Project Financing

Renovation

Our team calculated a renovation estimate for all of the subcategories outlined above in the methods sectionals can be seen in Table 4. In terms of ROI, operational cost savings would generate around \$34-\$38k annually, which was calculated by first estimating the EUI of Green Hall from average values for higher education buildings provided in literature and then multiplying by its gross square footage to get kWh used annually. We then used information from the Department of Energy (DOE) estimating that most commercial buildings see an average energy efficiency savings of 25% by upgrading to LEED gold standards (Dobiáš & Macek, 2014). Taking that difference in kWh used per year, we assumed the local energy utility company, Xcel Energy, charges an average commercial rate of \$0.10/kWh, which allowed us to estimate the savings accumulated per year. Formatting this into real ROI as a percentage given our estimated capital cost (discussed further below), we estimated a 0.00195% return annually. We acknowledge that this is typically considered an extremely poor ROI, but given that the building is not a value intended on creating an investment. This information is shared primarily for the sake of efficiency, and it is a useful metric to be used in comparing our two materials management methods. Although the SCC are not directly considered in ROI, they are accounted for in this subcategory as they serve as an indirect and negative return on the investment of the project. For renovation, given the very low amount of embodied carbon added to the total project output as discussed in the section above, there is a very low SCC associated, at an estimated - \$556 . This was found by multiplying the embodied carbon amount by the EPA's average value of \$46/ton CO₂e with an average 3% discount rate.

Subcategory	Metrics	Estimate	Additional Metric
Return on Investment (ROI)	Electricity Efficiency	\$17877 - \$19759 / Year	ROI 0.00195% / Year
	Natural Gas Efficiency	\$16241-\$17950 / Year	
	Social Costs of Carbon	-\$556.14	
Alternative Financing Options	Grants	Millions Available (DOE, Inflation Reduction Act)	High Opportunity Level
	Rebate Increase	19.9% rebate increase	
Capital Costs	Initial Capital Investment Renovation	\$15,891,572	Total Estimate \$19.66 Million USD
	Project Timeline	12 months	
	Initial Capital Investment Expansion	\$3,662,231	

Table 4: Renovation Financing Estimates for Green Hall

Capital costs for renovation were estimated using a study conducted by the University of North Texas on the average costs of renovating vs. demolishing and rebuilding their higher education facilities. Using our existing square footage estimate and the assumption of a 15% addition of new building space, we multiplied the values of \$613 (new construction) and \$399 (renovation) by the square footage estimates for each section and came up with a total cost estimate of roughly \$19.66 million for completing the project using this option (UNT, 2021). Additionally, relevant literature suggests that a project of this scope would on average take about 12 months to complete, not including the planning and drafting phase (Hale et al., 2009).

In terms of alternative financing options available for renovation, our team was able to discover a great number of opportunities available to finance a huge portion of the project. This is mainly due to the recent passing of the Inflation Reduction Act of 2022, which has given the DOE hundreds of millions of dollars to fund retrofitting operations targeting building efficiency and reduction of building operational impact (United States Department of Energy, 2023). Based on existing cases and grants that the DOE has given out in the past, it is highly likely that a renovation project on Green Hall could receive up to 25% of the upfront cost covered through a grant, which would equate to a few million dollars. Additionally, as a land grant institution, the University could file for a budget increase from the state to accommodate this project, however it

is unclear exactly how much might be feasible from this method. Due to the availability of very high dollar amount grants from multiple sources, we've categorized this method as having a high opportunity level for funding eligibility as seen in Table 4.

It is important to note that using these methods, there could be errors present in calculation from a number of factors. For efficiency savings, the average values do not take into account weather factors which oscillate energy usage intensity over the periods of seasonal changes. For the social costs of carbon, the values proposed by the EPA may change with each executive administration, as they are calculated in different ways. For rebates, each individual circumstance has variances in custom applications, so the values projected were only an average. Also, in terms of capital costs, these projections were only estimates based on average values for general higher education facilities. If someone were to use this framework with a bigger timeframe for their scenario, they would likely need to receive real bids on total cost before moving forward with a project.

Demolition and New Construction

The corresponding table showing the financial projections for demolition and new construction can be seen in Table 5. First looking at the ROI from efficiency upgrades, our team estimated about \$71.8k per year in savings, a great increase from the estimated amount for renovation. This is primarily due to the implication of renewables in any new LEED building as well as a hyper efficient heating and cooling systems in conjunction with energysmart appliances and LEDs. Similarly, this information was calculated using the same estimated EUI of Green Hall from average values for higher education buildings provided in literature and then multiplying by its gross square footage to get kWh used annually. We then used different information from the US Green Building Council (USGBC) and our literature review estimating an almost 50% increase in utility efficiency from the new building requirements for LEED listed above and their resulting improvements (Dobiáš & Macek, 2014). Using the average cost per kWh of \$0.10, we then extrapolated a decrease in consumption annually in the same manner to end up with that number. Given the greater savings but also greater capital costs, ROI from this method slightly increased to 0.002%. Because the embodied carbon added to the project's lifetime is so much higher within demolition and new construction, we saw a corresponding increase of project SCC to -\$2.633 million in damage to human health. This was done using the same value as the renovation projection.

Subcategory	Metrics	Estimate	Additional Application
Return on Investment (ROI)	Electricity Efficiency	\$37,637 / Year	ROI 0.002% / Year
	Natural Gas Efficiency	\$34,192 / Year	
	Social Costs of Carbon	-\$2,633,658.00	
Alternative Financing Options	Grants	\$50-100k State Level (Renewables)	Medium Opportunity Level
	Rebate Increase	9.90%	
Capital Costs	Demolition Expense	\$1.25 - \$4.97 million	Total Estimate \$36 million USD - \$41 million USD
	Project Timeline	1.5 - 4 years	
	Initial Capital Investment New building	\$35,096,059	

Table 5: Demolition & New Construction Financing Estimates for Green Hall

Within the demolition and new building process, there are a few additional capital costs incurred on top of construction itself. These come through the forms of demolition expenses, costs of new construction permitting, site surveying, demolition permitting, waste transportation, and architecture and design fees of the new building (Coelho & de Brito, 2011). Using existing estimates and input from experienced professionals on these costs, our team projected an additional cost of approximately \$1.25-\$4.97 million for these expenses on top of labor and materials costs. This was tagged on to the estimate for new construction costs completed using the same study from the University of Northern Texas estimating \$613 per square foot of a new lecture hall at our given gross square footage of 49,785 (UNT, 2021). The total projected bid combining these factors is between \$36 and \$41 million. The duration of project completion for demolition and new construction sees the largest increase over renovation, as it would take 2-4 years to complete based on project factors. This may mean it could take 4 times as long to demolish and build new than it would to renovate (Hale et al., 2009).

Looking at the alternative financing options for demolition of the existing building and building a new building, we see a great array of opportunities through the state of Minnesota to fund

individual improvement projects such as renewables or sustainable landscaping. These are more applicable to a new build, because a renovation likely would not involve new energy infrastructure or landscaping. Due to this, these state level opportunities are more within reach, however they don't have super high monetary value associated with them, and usually are only paid out in amounts less than \$100,000 (State of Minnesota, 2023). Even so, there is a chance that multiple grants could be secured giving a new building project a decent amount of funding opportunity. With good applications, it might see up to 10% of its cost offset. Due to the complexity of how private grants are secured, they are out of scope for this assessment, but may still be an option worth considering. Because rebates are primarily rolled out for improvements to existing energy infrastructure that reduces fossil fuels, a building using renewable energy won't see as high of an increase, which makes sense given the researched projection of an average 9.9% increase (USGBC, 2023). Because there are some good opportunities to get money back for a new building materials management method, we categorized it as having a medium opportunity level overall.

It should be taken into account that all of the opportunities for error in this case study discussed above in the renovation scenario all apply respectively for the same areas in this demolition and new building category. The projections for exact metrics in both cases were calculated in the same way and the same errors should be taken into account.

Scoring

Embodied Carbon Subcategories

Given that the embodied carbon impact category only has one subcategory, which is the total embodied carbon of the project, the difference in values of projected embodied carbon between each materials management method had a significant impact on the overall outcome of the tool. As discussed previously, the hypothetical renovation of Green Hall would only add a total of 12.1 projected metric tons of CO₂e emissions to the embodied carbon of the project's lifespan, whereas a demolition and new building scenario would more than double the total by adding an astonishing 1503.5 metric tons CO₂e (Table 2). This extreme difference was primarily thanks to Ferrock's carbon sequestering properties and material usage offsets from incorporating recycled steel (Table 2). This extreme difference made it easy to rank renovation as a 5/5 in comparison to demolition and new building which we scored as a 1/5.

Material Use and Disposal Subcategories

Looking at the material reusability subcategory, we can see that the demolition method is a clear winner for two reasons. Primarily, given the sheer quantity of new construction materials needed in order to complete the project, there is a far higher opportunity to potentially incorporate used

construction materials into the build, specifically through brick as discussed earlier. Second, the potential recyclability of the materials taken out of the existing building is quite high, as the brick removed from demolition could all be recycled. This amount could be a far higher quantity than the amount which would be recycled through renovation (Table 3), though we do acknowledge that fewer materials in general are needed for a building renovation. However, we also need to consider that leaving the bricks in use within a renovation project has value in itself. Due to this, neither option is close to perfect but demolition is much better than renovation, so we decided to score renovation 1.5/5 and demolition 3/5.

When we analyzed the feasibility of usage of sustainable materials within both materials management methods, there were several factors crucial to the overall score. First was the availability and cost feasibility of utilizing our identified ideal substitute for concrete (Ferrock) in either project. Because Ferrock is harder to obtain in large quantities and is more expensive, it would only be feasible in the expansion part of renovation, and not in an entire new building, as discussed earlier. Because of this, renovation would seem to have a higher performance in this area, however that is not considering the other many factors of a new building. Because a new building would entail replacing every single material in the project, we have to consider that decision makers would have complete end to end control over placing sustainable material alternatives throughout all the functions of a building other than its structure. New codes and performance standards for LEED requirements would dictate that a vast majority of these materials would be far more sustainable than those existing in Green Hall as it stands. Due to this, the demolition option would logically rank higher than renovation even with the Ferrock addition, so we scored renovation as a 2/5 and demolition/new building as a 4/5.

The opportunities for co-benefits of alternate materials usage in either option was viewed in a similar way to sustainable materials usage, due to the higher flexibility of the demolition option. For example, the demolition option would allow for a complete redesign of the building which could enhance natural light options, optimize future solar array performance, or allow space for sustainable landscaping features within its build (Balaban & Puppim de Oliveira, 2017). These co-benefits are those which cannot be quantified directly, but provide some measure of value to stakeholders based on the decisions made for material usage and placement within the final project. Renovation, on the other hand, may still have some opportunities for smaller benefits, such as larger windows or better designed common areas, but they would not be nearly as flexible or optimal as with demolition and new building. Because of this we've scored renovation at 2/5 and demolition and new building at a perfect 5/5 in this category.

In terms of total waste volumes, it was unsurprising to us that the renovation option outperforms the complete demolition of a building by a very high margin. As discussed earlier and as can be seen in Table 3, the net percent of project mass going to landfill is over triple the amount of renovation when a building is demolished. However, the renovation of a building still involves

the production of a significant amount of waste which cannot be reused or recycled or composted even in advanced industrial settings. We couldn't rank renovation perfectly as a result of this but it's almost there, so we scored it as a 4.5/5 whereas demolition performs so poorly in this category that we decided on a minimum score of 1/5.

Project Financing Subcategories

In terms of ROI, both methods failed to return value in any significant amount, with renovation sitting at a measly 0.00195% and demolition performing slightly better at 0.002%. However, the actual project amount of annual realized cost savings for demolition was almost double that of renovation (\$71k to \$39k), which is a significant amount that is made invisible given the corresponding nearly double increase in capital costs between the two projects. If we were only considering these factors in terms of ROI then demolition would have ranked higher, however we also included SCC as a consideration for ROI. Given the vast increase in social costs from renovation (-\$556) to demolition (-\$2.63 million), it was clear that renovation should slightly outrank demolition in this subcategory, although neither should be high given the low actual return (Tables 4, 5). Considering this, we gave renovation a 2/5 and demolition/new building a 1/5 (Figure 2).

When comparing capital costs for scoring, again there was a readily apparent difference between renovation and demolition, with the demolition and new building option cost projection (\$36-41 million) almost double the projected cost of renovating and expanding the existing building (\$19.66 million). Additionally, according to experts and the most relevant literature available, we expect that the time until project completion for demolishing and rebuilding would be 2 - 4x the duration of renovating and expanding which would likely be done in only about 12 months time. Considering this benefit and the cost contrast, but also the fact that the renovation costs are still a large amount of money which pose a significant barrier to enacting a sustainable building materials management method, we decided to score renovation substantially higher than demolition at 3.5/5 compared to 1.5/5 (Figure 2).

Assessing the available funding options was more difficult than assessing the previous two financing subcategories, given the uncertainty involved with the exact numbers the Green Hall project options might manage to get a hold of. It was clear that there were an equal amount of opportunities either way, however those provided by the federal government had a far higher dollar value associated with them. Because of the DOE's new initiatives for retrofitting buildings, the renovation option would be more likely to have a far higher amount of its upfront cost offset than the new building option, even though the opportunities available for a new building still exist from the state and local level. These opportunities are more geared towards smaller projects for new systems such as small renewable energy projects or sustainable landscaping projects. We also had to consider the greater increase in average rebate rates from

renovation (19.9%) than demolition and new building (9.9%) (Tablees 4, 5). Overall, renovation had better opportunities for cost offsets but also that there were still some opportunities and rebate benefits for new buildings, and therefore we ranked renovation at 4/5 and demolition at 2/5 (Figure 2).

Impact Category Weight Scores

When discussing the impact category weighting feature of the tool, it is important to understand that this is an adjustable feature and the specifications we set for our analysis of Green Hall are not meant to be used for every scenario. Some decision makers may choose to hold project financing factors to a much higher value than environmentally oriented ones, which is understandable, as long as consideration is being given to all impact criteria using the tool.

For the purposes of Green Hall, we decided to rank embodied carbon as our most important impact criteria at 50% of total project weight. This was primarily due to both our interests in climate change as a driving factor behind these decisions as well as the interests of our sponsor, the Minnesota Pollution Control Agency (MPCA), in conducting this research. The manufacturing industry contributes over 10% of the world's total emissions, and is the driving cause behind the embodied carbon of building materials (C2ES, 2023). One of the primary goals for this research has been to empower decision makers to reduce their organizations impact on climate change, so this weight is justified for our purposes.

We ranked material sustainability and disposal at 35%, the second highest impact criteria of the total project. This weighting was chosen because while climate change is the primary driving factor for our model, we could not ignore the detrimental impacts to the environment associated with the high volumes of landfilled waste from demolished buildings (Coelho & de Brito, 2012). It is estimated by the EPA that waste from construction and demolition of buildings accounts for up to 30% of all waste globally, meaning that it bears a large amount of responsibility for the environmental impacts stemming from landfilling and improper waste disposal. Additionally, we wish to promote the usage of sustainable building materials management methods as much as possible to allow for them to become mainstream and to reduce the harms of traditional materials management methods such as landfilling. As such, we feel justified for placing a high importance on this topic.

Project financing was weighed with the least importance at 15%. While the most ideal sustainable building solutions in the world could technically be implemented, they are oftentimes extremely costly and would never see the light of day in many situations. In our hypothetical scenario we have set an unlimited budget, however financing costs and funding opportunities bear a great impact on whether many of these projects ever see the light of day (Power, 2008).

Hence, we have weighed it lower than other factors in our analysis but it is still a primary aspect of the tool given its importance (Figure 2).

Analysis & Recommendation

The completed scorecard resulting from the analysis above can be seen as a whole in Figure 2. In terms of embodied carbon, we can unsurprisingly see renovation beat demolition and new building by a very wide margin due to their polar opposite values. Overall renovation is ranked 5/5 and demolition/new building is ranked 1/5. In the material sustainability and disposal category, demolition and new building beats renovation marginally due to the high level of opportunity for recycling, incorporation of sustainable materials and associated co benefits, even though there is a higher amount of net waste to landfill from this materials management method. This can be seen in their scores with renovation receiving 2.5/5 and demolition receiving 3.25/5 in this category on average. Under project financing, we see renovation beat demolition and new building once again thanks to the much lower associated upfront costs as well as the better array of opportunities from government funding agencies. This is expressed by renovations average value of 3.17/5 compared to demolitions average of 1.5/5.

Once these average values were filtered through the impact category assigned weights at the bottom of the tool, we can see our final results with renovation scoring a 3.85/5 and demolition and new building construction scoring 1.86/5. Based on these results, which sum our findings in a quantifiable manner, we would recommend proceeding with renovation of the existing building as a more sustainable and budget-friendly option. Given the objective of the tool, that is to incorporate and weigh the factors of sustainability into materials management methods decisions, we can say that it successfully carried out its task in quantifying our given methods in terms of how they meet our goals. If a different combination of weights was used for impact category importance, it is very likely that the two options might rank differently to one another, or closer to one another, at the very least. In a real decision making scenario, those in power could view the results of the inputs pertinent to their respective situations and use them to consider a more sustainable and efficient materials management method going forward.

Conclusion

An assessment of building materials management was conducted on Green Hall, a classroom-style building built in 1937 on the University of Minnesota Twin Cities campus. This assessment of Green Hall was hypothetical, with the overarching goal of creating a framework to use for future decisions made by Universities regarding their higher education buildings that have reached their “end-of-life”. The main deliverable of the project is the scoring tool with customizable weights. The assessment analyzed two “end-of-life” options for Green Hall, being a renovation and expansion, or a complete demolition of the current building to construct a new

“state of the art” building in its place. In the analysis, three main factors were examined, being embodied carbon, material usage and sustainability, and project financing. Subcategories for each of the factors were also analyzed. The scoring tool is adjustable for the goals of each project that it is used for based on the priorities and goals that are specific to the project, which assigns a score to the project based on the aforementioned factors and subcategories. For the specific case of Green Hall, it was found that the option that entails a renovation and expansion of the current building received a better score compared to the other option, with a score roughly two times greater than the path of demolition for a new building. Ultimately, the tool was successful in creating a quantitative analysis of the hypothetical case study, and as such we can conclude that it would be effective in applications to various other scenarios. The authors of this research hope to proliferate its usage in the future further by educating relevant decision makers through several available opportunities.

Appendices

Sustainability Scorecard

Criteria Scores		Scores Available from 1-5. Basis for scoring must be listed with specific examples.	
1. Embodied Carbon		Option #1	Option #2
Total Embodied Carbon		0.00	0.00
Average Score		0.00	0.00
2. Material Disposal and Sustainability		Option #1	Option #2
Reusability of Materials		0.00	0.00
Feasibility of Sustainable Material Usage		0.00	0.00
Opportunities for Cobenefits		0.00	0.00
Estimated Waste Volume		0.00	0.00
Average Score		0.00	0.00
3. Project Financing		Option #1	Option #2
ROI		0.00	0.00
Capital Costs		0.00	0.00
Available Funding Options		0.00	0.00
Average Score		0.00	0.00

*Change weights based on stakeholder impact category requirements. Total score should = 1.00

Weighted Criteria Scores	Weight	Option #1	Option #2
1. Embodied Carbon	0.33	0.00	0.00
2. Material Disposal and Sustainability	0.33	0.00	0.00
3. Project Financing	0.33	0.00	0.00
TOTAL SCORE	1.00	0.00	0.00

Figure 1: Blank Sustainability Scorecard

Sustainability Scorecard

Criteria Scores		Scores Available from 1-5. Basis for scoring must be listed with specific examples.	
1. Embodied Carbon		Demolition/New Bldg.	Renovation/Expansion
Total Embodied Carbon		1.00	5.00
Average Score		1.00	5.00
2. Material Disposal and Sustainability		Demolition/New Bldg.	Renovation/Expansion
Reusability of Materials		3.00	1.50
Feasibility of Sustainable Material Usage		4.00	2.00
Opportunities for Cobenefits		5.00	2.00
Estimated Waste Volume		1.00	4.50
Average Score		3.25	2.50
3. Project Financing		Demolition/New Bldg.	Renovation/Expansion
ROI		1.00	2.00
Capital Costs		1.50	3.50
Available Funding Options		2.00	4.00
Average Score		1.50	3.17

*Change weights based on stakeholder impact category requirements. Total score should = 1.00

Weighted Criteria Scores	Weight	Demolition/New Bldg. Weighted Score	Renovation/Expansion Weighted Score
1. Embodied Carbon	0.50	0.50	2.50
2. Material Disposal and Sustainability	0.35	1.14	0.88
3. Project Financing	0.15	0.23	0.48
TOTAL SCORE	1.00	1.86	3.85

Figure 2: Completed Scorecard for Green Hall

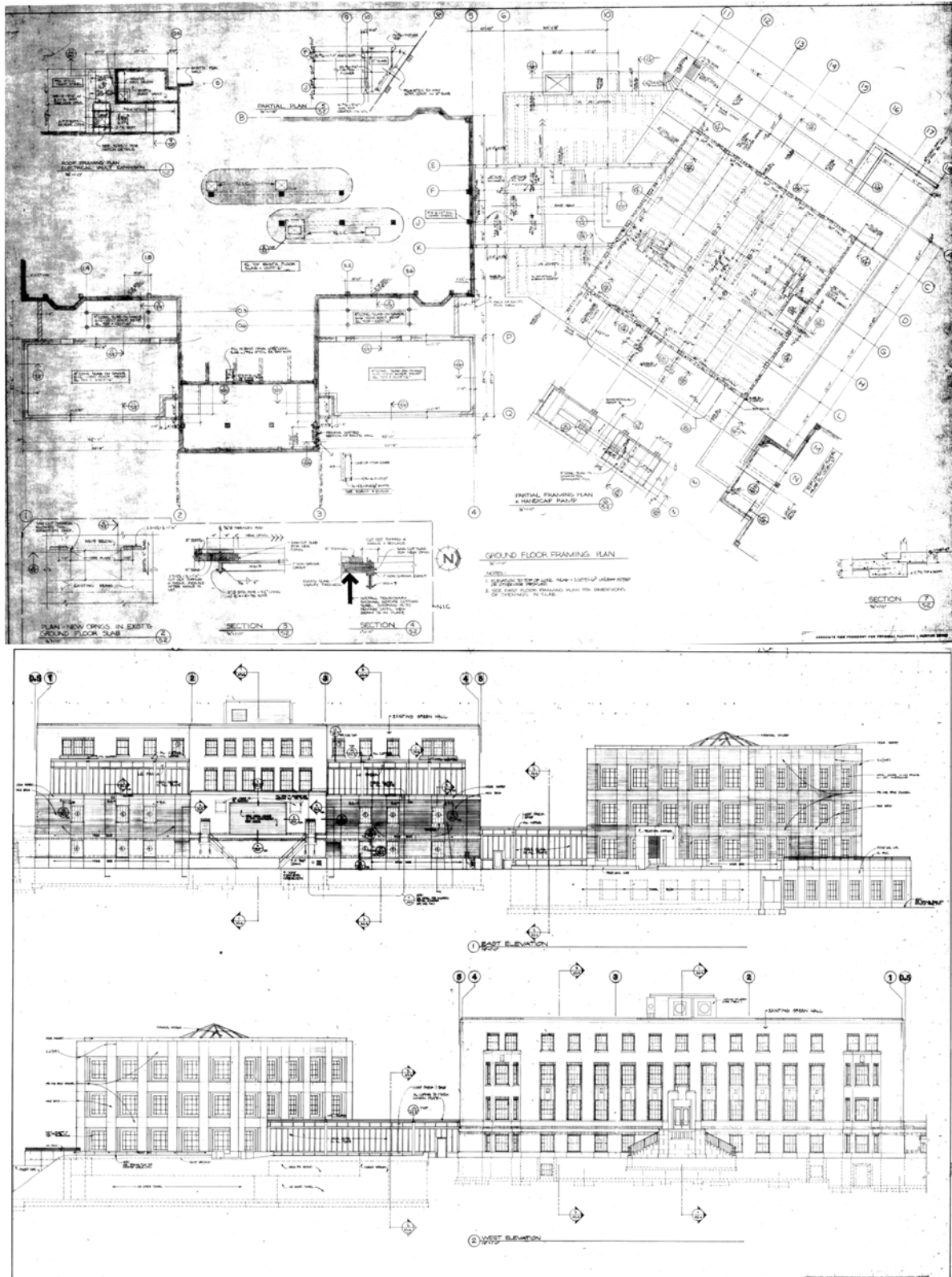


Figure 3: Sample Structural Documents for Green Hall

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