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Exploring Circular Economy Potential in Pittsburgh's Construction Industry

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EXECUTIVE SUMMARY

This report is the culmination of a 14-week coordinated research project conducted by 15 Master of Science in Architecture-Engineering-Construction Management (MS AECM) students at Carnegie Mellon University. Each fall semester, all graduating MS AECM students enroll in the *AECM Synthesis Project* course under the direction of Assistant Professor Joshua D. Lee. The course is designed to apply the diverse knowledge and skills that AECM students have acquired during their 16-month program to a critical public interest issue related to the built environment and the topics vary from year to year. In 2019 we focused on analyzing the environmental inequities in Pittsburgh schools. In the fall of 2020, we investigated the impact of COVID-19 on vulnerable communities. In 2021, we focused our efforts on understanding how deconstruction, as opposed to demolition, might reduce waste and provide new economic opportunities.

This year we engaged in five distinct investigations that explored a variety of ways Pittsburgh's design and costruction industry might move towards a Circular Economy. As defined by the Ellen MacArthur Foundation,

> *a circular economy is a systemic approach to economic development designed to benefit businesses, society, and the environment. In contrast to the 'take-make-waste' linear model, a circular economy is regenerative by design and aims to gradually decouple growth from the consumption of finite resources…*
>
> *The circular economy is based on three principles, driven by design: Eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature.*[1]

The semester began with a review of several reports on the global, national, and local Impacts of costruction waste. We then looked at existing onsite and offsite material recovery strategies and toured a CMU campus building under construction and Construction Junction, a local reseller of salvaged construction materials. Week 3 included a series of readings, discussions about Circular Economy, and an enlightening presenation by Guillermo Dekker, the Sustainable Cities & Regions Lead at Metabolic. Weeks 4 & 5 included an intense introduction to research methods and dividing the students into groups. These groups of two to five students then carried out six provocative studies organized into the following chapters.

Chapter 1 provides a prioritized list of technical, economic, environmental, social, and organizational barriers to inform policy makers of the varied priorities and perceptions of circularity, thereby paving a path for optimized decision-making and delegation of responsibilities in future projects. Chapter 2 presents a method of using LiDAR and BM technologies to analyze the feasibility of reusing materials in a dormitory slated to be removed in new construction. Chapter 3 analyzed the comparative advantages of using riveted, welded, and bolted connections in terms of their deconstructability. The findings indicate that bolted connections are the best option to opt for to maximize the steel reuse potential when compared with welding and riveting. Chapter 4 provides a deconstruction and life cycle assessment (Decon+LCA) of Pittsburgh's Environmental Charter School through several plausible end-of-life scenarios. The found that an optimized deconstruction process could reduce approximately 50% of greenhouse gas (GHG) emissions compared to full building

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[1] Ellen MacArthur Foundation. "Circular Economy Introduction." Accessed December 15, 2022. https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

demolition. The final chapter takes a step out and analyzed a variety of existing policy options for implementing a Circular Economy in Pittsburgh's construction industry. This study draws parallels between the CE strategies in the EU and the existing policies and initiatives in Pittsburgh to identify leverage points through which CE can be exercised in the city's built environment.

Together these reports provide preliminary but valuable insights that could aid stakeholders in the City of Pittsburgh make better decisions informed by the goals of ecological preservation, social benefits of a circular economy, as well as economic feasibility through enhanced public conversation.

ACKNOWLEDGEMENTS

This report would not be possible without the generous participation of Mike Gable, Executive Director at Construction Junction; Guillermo Dekker, the Sustainable Cities & Regions Lead at Metabolic; Beth A. Eckenrode, Co-founder of AUROS Group; the members of the AIA Pittsburgh Design + Research Group, and the anonymous interviewees. Financial support for printing and LiDAR scanning equipment was also provided by the School of Architecture at Carnegie Mellon University. Thank you to all!

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CHAPTER 1- BARRIERS TO ADOPTING CIRCULARITY PRINCIPLES FOR INSTITUTIONAL PROJECTS IN PITTSBURGH

Riti Anil Talreja & Ryan Vaz

CHAPTER SUMMARY

Over time, numerous strategies have been introduced that have the potential to fulfill the Circular Economy (CE) requirements in the construction industry. However, they have not been adopted widely due to a myriad of reasons such as the lack of familiarity, awareness, tools, and technology. Moreover, the management of a building from its conception to its demolition involves a wide range of stakeholders with different skills and stakes. The complex nature of relationships between stakeholders and the inherent lack of quantified data about the barriers facing the implementation of circularity emphasize the need for further research to identify the reasons behind the lack of its adoption.

This research aimed to identify these barriers and understand the impacts in relation to architects, contractors, and owner's representatives that work on institutional projects in Pittsburgh. The intent was to develop a weighted list of barriers that could be prioritized, highlight the gaps, and provide possible solutions to promote CE adoption in construction. We reviewed 10 papers that identified 30 commonly cited barriers across six categories--Economic, Social, Environmental, Technical, Organizational, and Political. Interviews with owners, architects, and contractors for projects within the Pittsburgh region helped identify the impacts of each of these categories and barriers.

Our research indicated that while there is industry-wide awareness of the concept, stakeholders still faced numerous challenges, preventing greater adoption of circularity. A weighted decision matrix was developed to prioritize these barriers, developing a comprehensive list to be tackled and encouraging the greater implementation of circular economy principles supported by metrics, tools, and guidance. Through these methods, we observed that technical and economic parameters were perceived to be the most influential while social and environmental factors were rated the lowest for their impact on material reuse. The uncertain composition and performance of salvaged materials along with the presence of lead and asbestos in structures was cited as a significant challenge. Along with the absence of incentives to design structures for the disassembly and reuse of materials at their end of life. The prioritized list developed is intended to inform policymakers of the varied priorities and perceptions of circularity, paving a path for optimized decision-making and delegation of responsibilities in future projects.

INTRODUCTION

Waste is generated throughout the life cycle of an asset. However, waste generated during construction, renovation and demolition, accounted for 600 million tons in 2020 for the United States alone.[2] This was a major contributor to the advent of Circular Economies (CE). Yet there is no consensus on a definition of the circularity of a building. A number of strategies have been introduced over the years that have the potential to fulfill the CE requirements. However, they have not been adopted widely due to a lack of familiarity with what the notion of the CE means for the AEC sector compared with the manufacturing industry.

> Construction and demolition waste makes up approximately 17.5% of Pennsylvania's municipal waste stream, with demolition accounting for 50% of all waste produced by the architecture, engineering, and construction (AEC) sector

The construction industry plays a critical role in transitioning to a Circular Economy since it is significantly more resource and material intensive than other industries. The construction sector consumes 42 billion tons of resources annually which accounts for about one-third of all global waste, most of which is not recycled or reused ending up in landfills.[3] Construction and demolition waste makes up approximately 17.5% of Pennsylvania's municipal waste stream, with demolition accounting for 50% of all waste produced by the architecture, engineering, and construction (AEC) sector.[4] These statistics are alarming and heighten the need for the implementation of a circular approach within construction. While efforts have been made to implement circularity and research has been conducted by companies such as Metabolic. Circularity in construction has not been explored to its full potential in Pittsburgh.

Pittsburgh is home to renowned educational institutions like Carnegie Mellon University and the University of Pittsburgh, together accounting for approximately 270 acres of land in the city, along with over 30 other universities and colleges making the presence of the educational industry an integral part of the city.[4] Pittsburgh is also among the leading cities for pediatric medicine and is home to some of the top hospitals specializing in women's health.[5] The two most prominent healthcare companies are UPMC and Allegheny Health Network. UPMC is the single largest private property owner in Allegheny County, with 656 acres worth $1.6 billion.[6] Hence, our study focuses on the barriers faced by stakeholders involved in the development of educational and medical facilities in the city.

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[2] Miller, Norman. "The Industry Creating a Third of the World's Waste." BBC Future. BBC, December 15, 2021. https://www.bbc.com/future/article/20211215-the-buildings-made-from-rubbish.

[3] Circle Economy. "Building a Circular Construction Sector Is Hard, but It Is Happening." Insights . Accessed December 13, 2022. https://www.circle-economy.com/resources/building-a-circular-construction-sector-is-hard-but-it-is-happening.

[4] "Construction and Demolition Waste." Department of Environmental Protection, 2011. https://www.dep.pa.gov/Business/Land/Waste/SolidWaste/MunicipalWaste/Construction-Demolition-Waste/Pages/default.aspx.

[5] Visit Pittsburgh. "Pittsburgh Industries & Corporations." Visit Pittsburgh. Accessed December 5, 2022.https://www.visitpittsburgh.com/meetpittsburgh/reasons-to-meet-in-pittsburgh/pittsburgh-industries-corporations/.

[6] "Living Large: On Property, UPMC Spends Big and Is Taxed Little." Pittsburgh Post Gazette, September 30, 2012. https://www.post-gazette.com/opinion/editorials/2012/09/30/Living-large-On-property-UPMC-spends-big-and-is-taxed-little/stories/201209300149.

LITERATURE REVIEW

The management of a building from its construction phase to its demolition involves a wide range of stakeholders with different skills and stakes, as illustrated by Charef and Lu.[5] The timescale of the different phases of a building's life cycle varies drastically and is considerably longer during its operation.

In response to the lack of consensus and to clarify the processes along the asset lifecycle, some authors have developed a classification of the current alternative design approaches to incorporate a more circular approach. This classification clarifies and illustrates the current diversity of existing alternative approaches with five central categories: prefabrication, design for change, design for deconstruction, reverse logistics, and closed-loop systems/cradle to cradle.[7] While this research has fueled the quest for clarity, there are still no studies that provide an overview of the barriers facing stakeholders while implementing sustainable strategies.

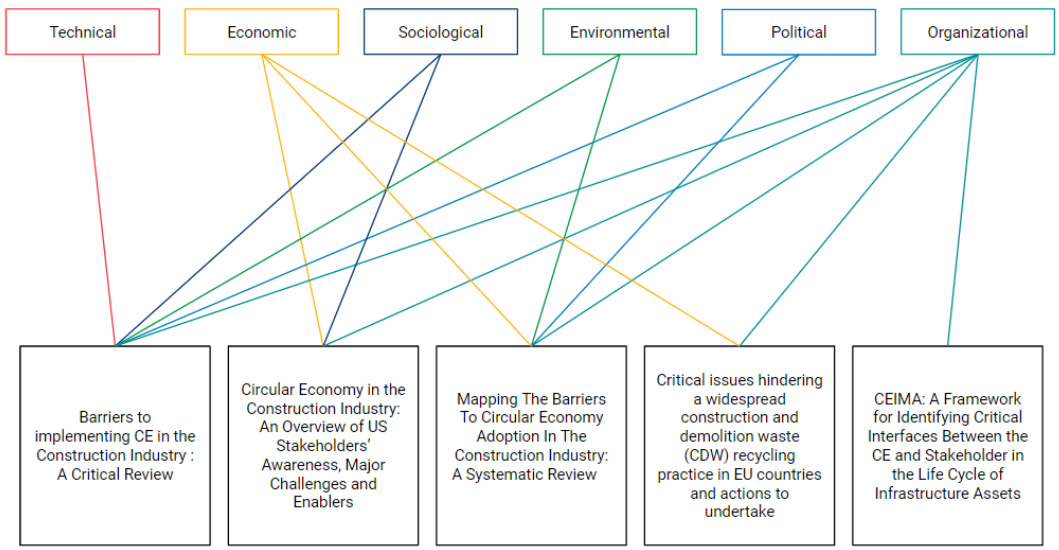

Figure 1.1: Literary Sources of Barriers

Barriers to CE in the AEC Industry

By referring to comprehensive precedents we infer that many of the challenges faced by stakeholders in adopting circular principles are often attributed to wider issues within the supply chain and construction industry. This hinders deeper analysis and structuring of barriers specific to circularity within project typologies and regions. The review examines and compares research situated in the U.S. and the European Union to identify differences in policy, culture and social conditions. A parallel approach to existing academic research identifies the classification of barriers and "stress points" for stakeholders in the industry. This provides a holistic outlook prior to identifying the gap statement.

In another study, various papers establish an understanding of the barriers identified in the literature that are hindering the development of the CE in the AEC

[7] Charef, R.; Lu, W. Factor dynamics to facilitate circular economy adoption in construction. J. Clean. Prod. 2021, 319, 128639. https://doi.org/10.1016/j.jclepro.2021.128639

sector.[8] These barriers include a myriad of limitations cited by various stakeholders during different stages of the building's life cycle. The author classifies these limitations into categories to facilitate the analysis. The six main categories used are economic, social, political, organizational, technological and environmental. This classification by discipline allows us to weigh and highlight the various issues relating to processes, communication, implementation, lack of knowledge and required data etc. The interrelation between the barriers from different categories is very common due to the holistic nature of the construction lifecycle. Organizational barriers were most cited, highlighting the difficulty with changing the working methods and managing the required teamwork and a multidisciplinary approach.

Wuni conducted a systematic literature review of over 50 research articles on barriers to circularity within the construction industry and provides an understanding of academic interpretation of the barriers and their influence on the decision-making process.[9] Based on the frequency of citation, these factors are grouped into 11 taxonomies. Further, the author prioritizes these barriers through a method known as pareto analysis. The Pareto Principle states that 80 percent of benefit comes from 20 percent of the work. Or, conversely, that 80 percent of problems can be traced back to 20 percent of causes. Of the 10 barriers with the highest citations, economic and regulatory categories formed a majority of the classification, followed by knowledge and management. In addition to this, the research proposes a strategy map of countermeasures to mitigate the barriers in adopting CE within the construction industry. Stakeholder awareness on circular materials and strategies was the fourth most-cited barrier in the study. The research, however, relies on citation frequencies which does not give weightage to owners and other stakeholders in each context. This would mean that even though stakeholders rank a certain barrier higher than others, it may not be prioritized if the barrier does not feature in others' research.

To draw parallels from the European context, the critical issues hindering a widespread construction and demolition waste recycling perspectives from a stakeholder perspective rely on stakeholder surveys and interviews to derive a list of challenges.[10] The participant group included owners, policy makers, designers and construction professionals along with representatives of the recycling and waste management industries. Similar to previous studies, stakeholders prioritized environmental benefits and reduction of material generation over technical aspects. However, saving on transportation and disposal costs was another key reason to implement recycling and reuse. An analysis of stakeholders' opinions of barriers emphasize the problem with regulations surrounding waste management and its use. Use of the term "End-of-Waste" to establish criteria was a key demand of stakeholders from the recycling and manufacturing industry who participated in the survey. Incentivizing reuse and recycling within construction along with designing frameworks and policies to guide the industry were other demands raised. Based on these results, the author recommends three methods of intervention, 1) Standardization of frameworks and terminology across member states, 2) establishment of a robust tracking system, and 3) segregation in batches at centralized plants. However, with an uneven number of stakeholders

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[8] Charef, Rabia, Jean-Claude Morel, and Kambiz Rakhshan. 2021. "Barriers to Implementing the Circular Economy in the Construction Industry: A Critical Review" Sustainability 13, no. 23: 12989. https://doi.org/10.3390/su132312989

[9] Wuni, I. Y. (2022, July 31). Mapping the barriers to circular economy adoption in the construction industry: A systematic review, pareto analysis, and mitigation strategy map. Building and Environment. https://doi.org/10.1016/j.buildenv.2022.109453

[10] Luciano, A., Cutaia, L., Altamura, P., & Penalvo, E. (2022, July 14). Critical issues hindering a widespread construction and demolition waste (CDW) recycling practice in EU countries and actions to undertake: The stakeholder's perspective. Sustainable Chemistry and Pharmacy. https://doi.org/10.1016/j.scp.2022.100745

representing each group, the research would be skewed with biased analyses and outcomes.

AEC Collaboration

Collaboration between different stakeholders along the construction value chain is essential to develop a fully circular built environment.[11] Investigating the state of practice of circular strategies adoption is necessary in order to pinpoint current barriers and enablers for a transition towards a CE model in the built environment in the U.S. This study assessed U.S. architecture, engineering, and construction (AEC) industry stakeholders' awareness of CE in the construction industry to better understand the major challenges and enablers of adopting circular strategies in construction projects. The most significant challenges identified were related to budget and upfront costs, lack of awareness and CE education, lack of policies, and changes required in current construction business models. Lack of capital and upfront costs is a barrier largely cited in the literature, and such a barrier is especially evident in small and medium-sized enterprises.[12] The study highlighted a vast gap in the awareness of the circular concept amongst the main stakeholders. Notably, while a lack of CE knowledge is a barrier, good awareness of CE alone does not necessarily translate into a company's willingness to adopt CE principles.

The most significant challenges identified were related to budget and upfront costs, lack of awareness and CE education, lack of policies, and changes required in current construction business models

Market Conditions

Market conditions such as consumer demand and economic attractiveness are necessary for a transition towards circularity.[13] One market condition that may represent a barrier to circularity is the lower price of virgin materials when compared to recycled materials.[14] Finally, regulatory barriers are another highly discussed theme in the CE literature. Specifically, in the U.S. context, it recognizes the lack of consistency in environmental regulations at the city, state, and federal levels[15] – e.g. states like California, Colorado, and Washington have higher environmental consciousness and more initiatives to address built environment issues than other states.[16]

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[11] Zimmann, R., H. O'Brien, J. Hargrave, and M. Morrell. "The circular economy in the built environment." Arup: London, UK (2016).

[12] Rizos, Vasileios, Arno Behrens, Wytze van der Gaast, Erwin Hofman, Anastasia Ioannou, Terri Kafyeke, Alexandros Flamos, et al. "Implementation of Circular Economy Business Models by Small and Medium-Sized Enterprises (Smes): Barriers and Enablers." Sustainability 8, no. 11 (2016): 1212. https://doi.org/10.3390/su8111212 .

[13] Kirchherr, Julian, Denise Reike, and Marko Hekkert. "Conceptualizing the Circular Economy: An Analysis of 114 Definitions." Resources, Conservation and Recycling 127 (2017): 221–32. https://doi.org/10.1016/j.resconrec.2017.09.005

[14] Mont, Okansa, Andrius Plepys, Katherine Whalen, and Julia L.K. Nußholz. "Business Model Innovation for a Circular Economy: Drivers and Barriers for the Swedish Industry – The Voice of Rees Companies." Lund University, 2017. https://portal.research.lu.se/en/publications/business-model-innovation-for-a-circular-economy-drivers-and-barr/fingerprints/

[15] Pushkar, S., and E. Shaviv. "Using Shearing Layer Concept to Evaluate Green Rating Systems." Architectural Science Review 59, no. 2 (2014): 114–25. https://doi.org/10.1080/00038628.2014.966051

[16] One Planet Network (OPN), 2020. State of Play for Circular Built Environment in North America. Yale Center for Ecosystems in Architecture, Yale University.

PROBLEM STATEMENT & RESEARCH QUESTION

The complex nature of relationships between stakeholders and the inherent lack of quantified data about the barriers facing the implementation of circularity, emphasize the need for research to identify the reasons for the lack of adoption of this approach. Siloed working methods with the division of stakeholders within particular phases, with poor communication, further hamper the streamlining of circular processes. Therefore, the various barriers will be divided into macro-categories, motivated by the need to cover the whole lifecycle of the asset and all stakeholders involved in the asset lifecycle in line with the holistic approach required to implement a CE.

This research aims to identify the barriers faced by stakeholders while adopting CE strategies and understand their dynamics. The intent is to develop a weighted list of barriers that can be prioritized based on the collective goals of all stakeholders.

Therefore, our research is guided by the following question:

What are the barriers faced by stakeholders of institutional projects while adopting circularity principles for construction projects in Pittsburgh?

METHODOLOGY

Studies on Individual perceptions rely on collecting data from well-informed participants that are representative of wider groups. As the topic relies on accurate interpretation and analytics of unevenly quantified data, any gaps that exist must be filled through alternative sources of data, calling for a multi-step approach to data collection and analysis. This ensures that data can be validated and compared at every stage for uniformity in results.

Prior to the collection of stakeholder inputs, a list of barriers across various typologies was collated through literature reviews of existing research within similar constraints of our study. The taxonomy established by Charef and Morel served as the underlying framework to organize barriers. Other studies create a similar system with variations in terminology or sub-classification. However, the specific nature of the groups ensures minimal overlap of barriers, optimizing the process of analysis and interpretation of results. The six categories, shown in Figure 1.2, are Economic, Social, Environmental, Technical, Organizational, and Political. Barriers were then classified into these broad categories and standardized based on relevance. Interviews were then conducted with a select group of stakeholders across various organizations involved in the construction of institutions within Pittsburgh. Data collected from these interviews were processed through a Weighted Decision Matrix analysis to prioritize the barriers according to the weights assigned to the categories by the stakeholders themselves.

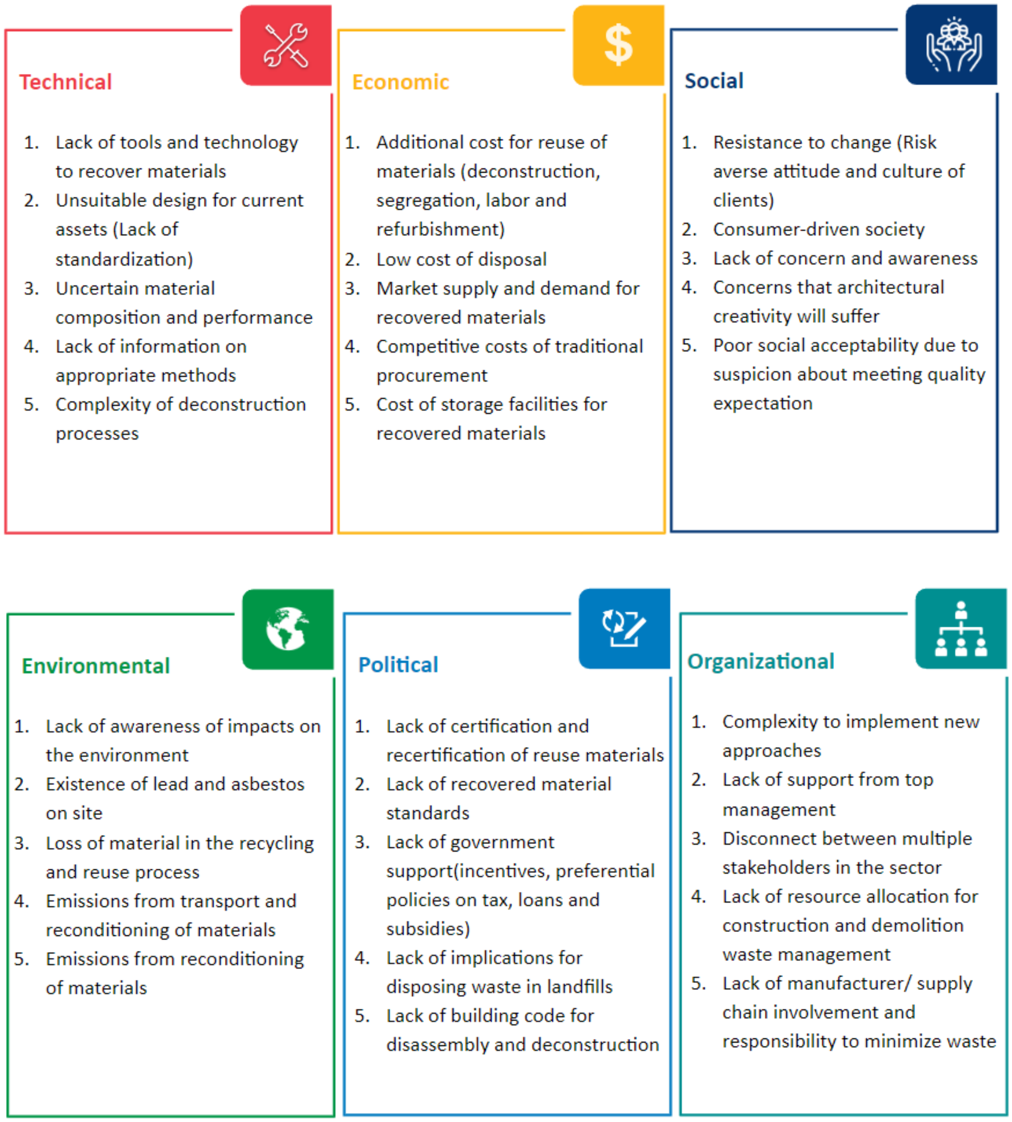

Figure 1.2: List of Barriers within the six categories

Interviews

An equal number of owners, architects, and contractors for projects within the Pittsburgh region were interviewed in individual sessions. As the study is contextually limited to institutional projects, interviews were conducted with stakeholders from higher education and medical projects. Figure 1.3 lists the organizations represented by the participants in the study and their role within their project. The participants' names are withheld from the study and their opinions are not representative of their respective organizations.

Stakeholder Category	Organization
Owner's Representative	Campus Design and Facility Development (CDFD) at Carnegie Mellon University
Owner's Representative	Campus Design and Facility Development (CDFD) at Carnegie Mellon University
General Contractor / Construction Manager	PJ Dick - Trumbull - Lindy Group
General Contractor / Construction Manager	Mascaro Construction
Design Architect	Ex - Perkins Eastman
Design Architect	Smith Group

Figure 1.3: Participant List for Stakeholders in Medical and Educational Projects

A baseline of participant awareness was also established wherein each participant was given the opportunity to describe any strategies related to circular economies that they may be aware of or used in a project. The answers were grouped and categorized based on formal strategies currently incorporated into circularity models. Strategies that did not directly translate to a formally defined barrier were added to the list; subject to relevance. Participants were asked about what happens to waste in their construction and demolition projects and the reasons behind the diversion plan implemented. This provided additional information on how informed stakeholders are on the C&D waste management practices that can be employed or the issues they face in implementing them.

The interview is divided into three parts:

- Participant awareness of waste management strategies
- Prioritization of barrier categories based on their impact on the project
- Selection of influential barriers within each category

Weighted Decision Matrix

Data from the interviews were weighed and interpreted through a set of choices against a set of criteria. This decision-making tool was developed by Stuart Pugh to compare multiple options based on specific weights assigned to each option. As each of the alternatives is weighed individually, changes to weightage directly influence the prioritization of options. For this study, weights were assigned to each category based on input from stakeholders. The weightage of the barrier, therefore, directly influences the ranking of each individual barrier.

Weighted decisions for given criteria (C) are calculated by using the formula:

Weighted Alternative = $W_C \times CS_x$

Where W_C = Weightage assigned to the criteria

CS_x = Criteria Score for the specified alternative

FINDINGS

Circularity Strategies Used by Participants

Participants of all companies and stakeholder categories have prior experience in material reuse and could identify strategies that have been deployed in institutional projects. Amongst 11 strategies that were identified, four strategies related to waste management and diversion were referenced by five participants, highlighting an active effort to optimize material use and salvage of material with the greatest potential during construction and demolition processes. Strategies that are to be implemented at the concept and schematic design stages were rated the least as the primary focus for stakeholders of educational and medical focus is longevity and resilience of structures while optimizing budget. Due to this, participants stated that design for deconstruction and reconfigurability are not commonly deployed for these project typologies. Additionally, the implementation of lean construction principles and incentives provided to green-certified buildings promote waste management and reduction on site. The number of votes received by each strategy is provided in Figure 1.4.

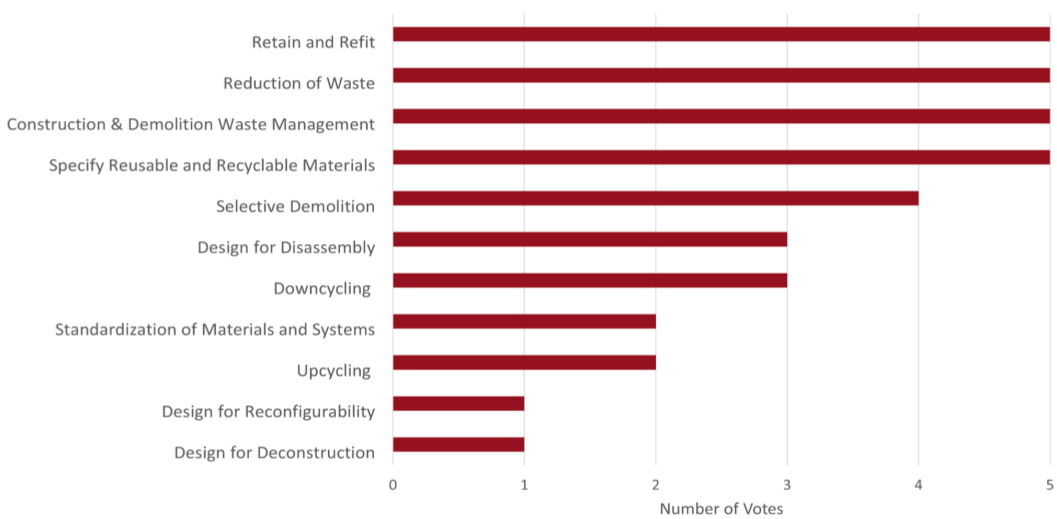

Figure 1.4: Participants Familiar with Circularity Strategies

Barrier Weightage

Participants were asked to provide a specific weightage for each category of barriers listed previously, based on their understanding of the term. The weights were provided on a scale of 1 - 5, with 1 being not at all impactful and 5 being very impactful.

As shown in Figure 1.5, owners consistently rated technical and economic barriers as extremely impactful, with the highest priority being assigned to them. Organizational barriers followed with an average rating of 4.5, reflecting challenges in decision-making and policies within team structures. On the other hand, the effective adoption of sustainability principles at the early stages of a project has led to lesser challenges at later stages, reducing the impact of environmental barriers in adopting circular economies. Education and medical institutions are often non-profit organizations that can leverage tax exemptions and subsidies. This creates a lack of incentives and penalties that would encourage the adoption of circular principles by organizations.

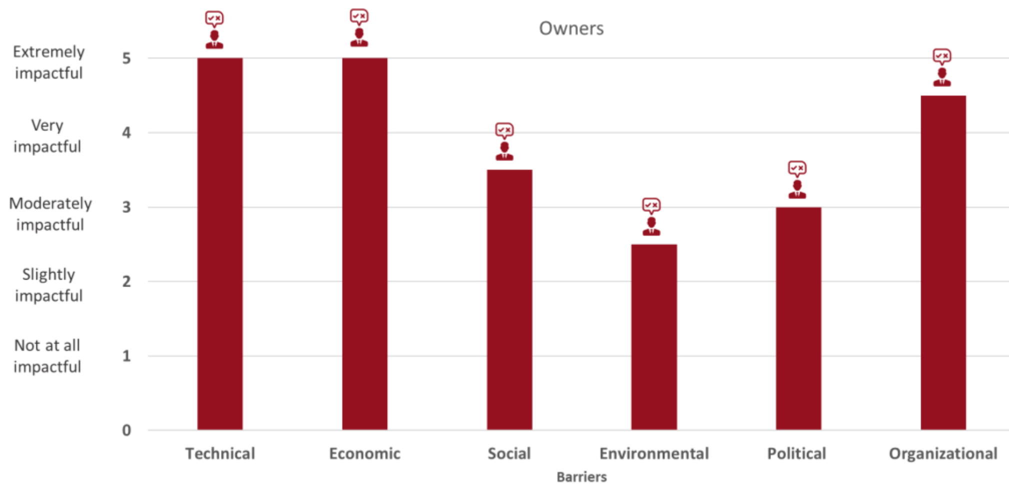

Figure 1.5: Owners Perception of Barrier Categories

Prioritization and weightage of barriers by architects displayed a variance in the impact of environmental and organizational barriers when compared to owner-assigned weights. Figure 1.6 shows the votes provided to all six barrier categories by architects through individual interviews. Organizational barriers were stated to be moderately impactful and the least when compared to other barriers as architects cite owners' policies and direction as constraints on the material specification for the given building types. However, technical and political barriers were perceived to have the greatest impact on implementing circularity on the basis of relevant building codes or the lack thereof. Public perception and broader community goals have led to greater concern and focus on social and environmental factors that influence circularity.

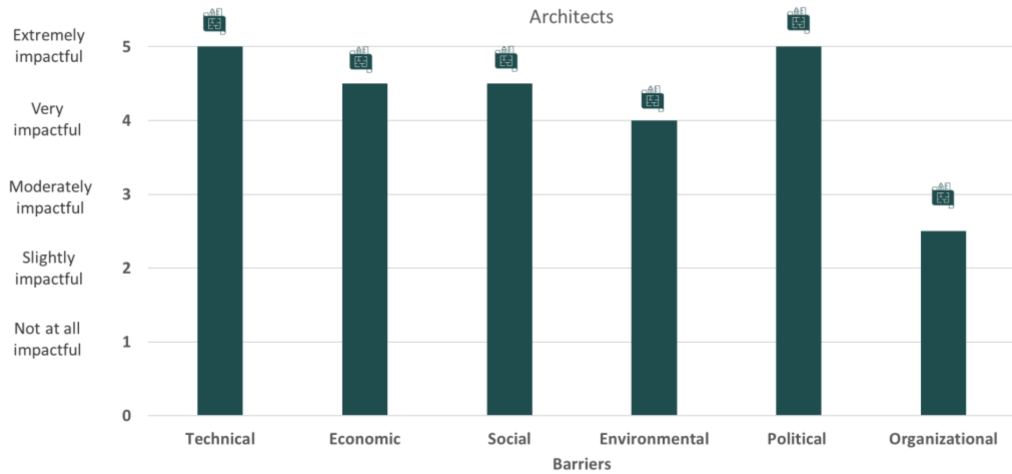

Figure 1.6: Architects Perception of Barrier Categories

Contractor perceptions followed a similar trend on the importance of technical and economic barriers, receiving the highest rating along with organizational barriers. social barriers, however, were perceived to be less impactful as the onus on mitigating these barriers falls on the design team. Contractors' prioritization of quality and cost, along with contractual obligations towards the necessary specifications of each material influence the weights of each barrier classification. Figure 1.7 depicts the votes given by contractors through their interviews.

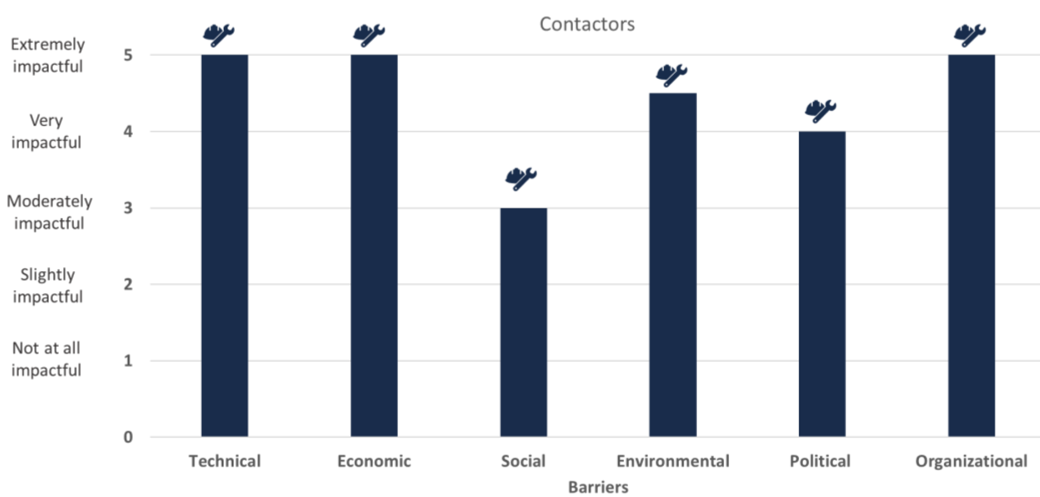

Figure 1.7: Contractors Perception of Barrier Categories

A weighted decision matrix requires a singular weightage to be assigned for each of the 6 categories of barriers. To achieve this, while ensuring uniformity, an average of all participant responses is calculated and input into the matrix. The table below collates all responses and provides an average that can be assigned as the weight of each category. Technical barriers are given the highest weightage due to the consistently high number of votes provided by all participants. Similarly, economic barriers have the second highest weightage with a relatively low variation in weights assigned by participants. social, environmental, and political barriers have a low weightage assigned due to a high degree of variance in participant opinions.

Table 1.1: Weightages Assigned to Each Category of Barriers

Barriers	Owner 1	Owner 2	Contractor 1	Contractor 2	Architect 1	Architect 2	Total	Weightage
Technical	5	5	5	5	5	5	30	5.0
Economic	5	5	5	5	4	5	29	4.8
Social	4	3	3	3	5	4	22	3.7
Environmental	3	2	5	4	5	4	23	3.8
Political	2	3	3	5	5	5	23	3.8
Organizational	4	5	5	5	3	3	25	4.2

Barrier Prioritization

Participants were asked to elaborate on their weights and the specific challenges they faced under each category. Their responses were interpreted as an individual vote for a specific barrier that matches or closely relates to their description of the challenge. In cases where participants mentioned over three individual barriers, participants were asked to prioritize their responses and provide their top three barriers to maintain consistency in the number of votes.

Within technical barriers, uncertain material composition and its current performance received the highest score, in line with comments provided on the weightages of barrier categories. Participants also raised concerns about the lack of available tools and technologies within Pittsburgh along with information about the process to be followed while extracting reusable materials. The complexity of the deconstruction process received the lowest votes with no mention of the extraction process during interviews with architects. Votes received for each individual technical barrier are shown in Table 2 below.

Table 1.2: Prioritization of Technical Barriers

Technical	Contractors	Architect	Owners	Total
Lack of tools and technology to recover materials	1	1	2	4
Unsuitable design for current assets (Lack of standardization)	2	1		3
Uncertain material composition and performance	1	2	2	5
Lack of information on appropriate methods	1	2	1	4
Complexity of deconstruction processes	1		1	2

Economic barriers received varied scores as the scope and priorities of all stakeholders differ from one another. Additional costs associated with reusing materials were mentioned by all contractors and architects but were not a concern for owners. This inversely relates to the competitive costs of traditional procurement, a broader area of focus for owners. Market supply and demand for recovered materials received the highest number of votes amongst economic barriers while the cost of storage for such materials was referenced the least number of times.

Table 1.3: Prioritization of Economic Barriers

Economic	Contractors	Architect	Owners	Total
Additional cost for reuse of materials (deconstruction, segregation, labor and refurbishment)	2	2		4
Low cost of disposal	1	1	1	3
Market supply and demand for recovered materials	2	2	1	5
Competitive costs of traditional procurement		1	2	3
Cost of storage facilities for recovered materials	1		1	2

Participants rated resistance to change and poor social acceptability as the most impactful social barriers reflecting a negative perception of material reusability within the market. On the other hand, concern among stakeholders for the environment and awareness of the impacts of material reuse were rated low. This indicates a high degree of awareness within the construction industry of the reasons for implementing circularity principles in construction. Varied responses were received from stakeholders on whether architects would feel like circularity and a fixed material list would stifle creativity, with none of the architects agreeing with this opinion. The table below shows the number of votes received for each social barrier.

Table 1.4: Prioritization of Social Barriers

Social	Contractors	Architect	Owners	Total
Resistance to change (Risk averse attitude and culture of clients)	1	2	2	5
Consumer-driven society and lack of demand for reuse products	1	1	1	3
Lack of concern and awareness	1	1		2
Concerns that architectural creativity will suffer	2		1	3
Poor social acceptability due to suspicion about meeting quality expectations	1	2	2	5

The existence of hazardous substances in extracted materials is perceived as the greatest barrier to material reuse across all categories. Every participant ranked this at the top of their concern within the environmental category and spoke of the need for abatement and testing prior to deconstruction. Most educational and medical buildings contain asbestos or lead due to the prolonged lifespan of these structures and the inadvertent use of such substances during their construction or renovation. Such buildings may also lack documentation to identify material composition prior to testing, introducing this barrier as an uncertainty. Emissions from the transport and reconditioning of such materials received the lowest votes as the participants compared benefits against emissions from traditional manufacturing and procurement.

Table 1.5: Prioritization of Environmental Barriers

Environmental	Contractors	Architect	Owners	Total
Lack of awareness of impacts on the environment		1		1
Existence of lead and asbestos on site	2	2	2	6
Loss of material in the recycling and reuse process		1	2	3
Emissions from transport of materials	1		1	2
Emissions from reconditioning of materials	1	1		2

The lack of certification and standardization procedures of materials was a major concern for contractors and architects who would need to verify quality as they bear the cost and risks if any issues arise during its reuse. Mixed responses on government support can be attributed to the non-profit status of most institutions. This reduces the influence of subsidies and benefits that currently exist during the decision-making process. Table 6 below indicates the number of participants who voted for each barrier within the political category.

Table 1.6: Prioritization of Political Barriers

Political	Contractors	Architect	Owners	Total
Lack of certification and recertification of reuse materials	2	2		4
Lack of recovered material standards	2	2		4
Lack of government support(incentives, preferential policies on tax, loans and subsidies)	2		1	3
Lack of implications for disposing waste in landfills		1	1	2
Lack of building code for disassembly and deconstruction		1	1	2

Participants shared complicated and interlinked responses to organizational barriers, with stakeholders having differing opinions as these barriers are driven by the project team and the organization itself. Lack of support from top management and allotment of resources towards this process is considered the top organizational challenges faced by stakeholders. However, the disconnect between stakeholders and the contractor's ability to handle such waste is not seen as a major barrier and received the lowest votes within the category. Table 7 captures the votes received by each barrier by individual stakeholders.

Table 1.7: Prioritization of Organizational Barriers

Organizational	Contractors	Architect	Owners	Total
Complexity to implement new approaches	2		1	3
Lack of support from top management	1	2	1	4
Disconnect between multiple stakeholders in the sector	1			1
Lack of resource allocation for construction and demolition waste management	1	1	2	4
Lack of manufacturer/ supply chain involvement and responsibility to minimize waste	1	1	1	3
Contractor's ability to handle deconstruction/		1		1

DISCUSSION AND SIGNIFICANCE

Our research indicated that while there is industry-wide awareness of the concept of circularity, stakeholders still faced numerous challenges, preventing greater adoption. All stakeholders were in consensus about the most impactful barrier categories being technical and economic, however, their perceptions about the other categories varied.

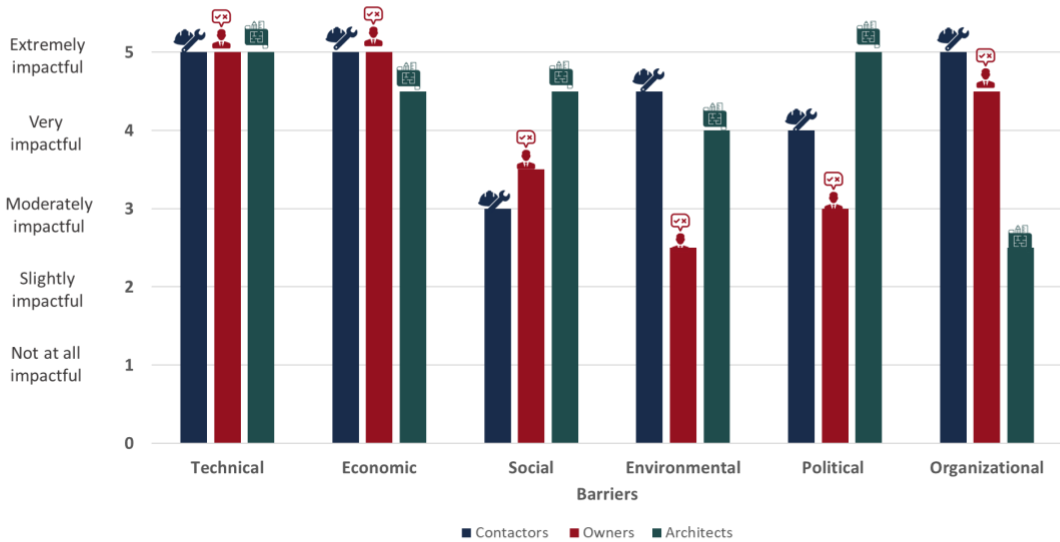

Figure 1.8: Comparative of Stakeholders' Prioritization of Barrier Categories

The competitive cost of traditional procurement was cited as a barrier by owners and architects, conversely, not contractors. This was credited to the provision of specifications by architects which is reliant on the owner's budget and quality requirements and not solely on the cost of procurement. Similarly, while contractors and owners believed that concerns regarding the stifling of architectural creativity by employing salvaged materials was a potential barrier, architects believed that it was not a hindrance. They believed that the wide range of materials available today provided them with an opportunity to explore beyond conventional materials. Additionally, while architects and contractors were concerned about design incentives and certifications available for reused materials as the onus for construction quality and safety lies on them, similar concerns were not specified by owners. Most educational and medical institutions in Pittsburgh are non-profit organizations and are exempt from a number of taxes, consequently, incentives in the form of tax credits are not applicable. The findings from our research highlight the inherent difference in organizations and the interests of the different stakeholders. Although this difference in perceptions is inevitable, it can raise challenges. Aligned interests among stakeholders can encourage collaboration and work towards similar goals. Conducting workshops and seminars to educate all stakeholders and the general public could be beneficial.

The findings from our research highlight the inherent difference in organizations and the interests of the different stakeholders.

Table 1.8 below depicts the prioritized list of barriers

	Barrier	Category	Weightage	Votes	Weighted Average
1	Uncertain material composition and performance	Technical	5	5	**25**
2	Market supply and demand for recovered materials	Economic	4.8	5	**24**
3	Existence of lead and asbestos on site	Environmental	3.8	6	**22.8**
4	Lack of tools and technology to recover materials	Technical	5	4	**20**
5	Lack of information on appropriate methods	Technical	5	4	**20**
6	Additional cost for reuse of materials (deconstruction, segregation, labor and refurbishment)	Economic	4.8	4	**19.2**
7	Resistance to change (Risk averse attitude and culture of clients)	Social	3.7	5	**18**
8	Poor social acceptability due to suspicion about meeting quality expectations	Social	3.7	5	**18**
9	Lack of support from top management	Organizational	4.2	4	**17.6**
10	Lack of resource allocation for construction and demolition waste management	Organizational	4.2	4	**17.6**
11	Unsuitable design for current assets (Lack of standardization)	Technical	5	3	**15**
12	Lack of certification and recertification of reuse materials	Political	3.8	4	**14.4**
13	Lack of recovered material standards	Political	3.8	4	**14.4**
14	Low cost of disposal	Economic	4.8	3	**14.4**
15	Competitive costs of traditional procurement	Economic	4.8	3	**14.4**
16	Complexity to implement new approaches	Organizational	4.2	3	**13.2**
17	Lack of manufacturer/ supply chain involvement and responsibility to minimize waste	Organizational	4.2	3	**13.2**
18	Loss of material in the recycling and reuse process	Environmental	3.8	3	**11.4**
19	Consumer-driven society and lack of demand for reuse products	Social	3.7	3	**10.8**
20	Concerns that architectural creativity will suffer	Social	3.7	3	**10.8**
21	Lack of government support(incentives, preferential policies on tax, loans and subsidies)	Political	3.8	3	**10.8**
22	Complexity of deconstruction processes	Technical	5	2	**10**
23	Cost of storage facilities for recovered materials	Economic	4.8	2	**9.6**
24	Emissions from transport of materials	Environmental	3.8	2	**7.6**
25	Emissions from reconditioning of materials	Environmental	3.8	2	**7.6**
26	Lack of concern and awareness	Social	3.7	2	**7.2**
27	Lack of implications for disposing waste in landfills	Political	3.8	2	**7.2**
28	Lack of building code for disassembly and deconstruction	Political	3.8	2	**7.2**
29	Disconnect between multiple stakeholders in the sector	Organizational	4.2	1	**4.4**
30	Contractor's ability to handle deconstruction/	Organizational	4.2	1	**4.4**
31	Lack of awareness of impacts on the environment	Environmental	3.8	1	**3.8**

Technical Barriers

Among technical barriers, uncertain composition and performance were cited as the greatest barrier to reusing materials. Materials not only determine the visual component of a structure but also greatly contribute to the health and safety of its occupants. Most materials specified for projects that are traditionally procured are certified and information about their quality is provided, giving stakeholders an insight into material performance under real-life service conditions. However, such data is not readily available for salvaged materials causing concerns about off gassing and deleterious effects on the health of construction workers and occupants. Additionally, stakeholders communicated a lack of access to information about appropriate methods and the tools and technology to retrieve and reuse materials. This highlights a gap that can be bridged with the help of seminars and workshops by consultancies such as Metabolic and organizations like Construction Junction to create awareness of the available resources and their potential uses. Furthermore, software such as Building Information Modeling, utilized frequently in construction projects, can be employed to quantify, document, and create material passports for individual structures as demonstrated in Chapter 2.

Economic Barriers

Cost was cited as the underlying cause for most barriers by all stakeholders. The construction industry is highly sensitive to the forces of supply and demand. Interview participants cited a lack of market supply and demand for recovered materials as the most impactful economic barrier. Most institutional projects are developed on a large scale and procuring salvaged materials for such projects is not feasible. However, these projects have contributed to material salvaging warehouses such as Construction Junction and Doors Unhinged providing surplus materials from demolition projects.

Furthermore, the industry is highly volatile, and fluctuations in the prices of materials and labor directly impact the outcome of such projects. The implementation of circular economy principles is seen as a cost and workforce-intensive endeavor, which can equate to a lot of work for little to no reward for stakeholders, thus hindering widespread adoption.

Social Barriers

In the construction industry implementation of new processes in procuring, contacting, and managing requires a concerted change management effort. The traditional approach of the industry makes it resistant to change, which is the most significant social barrier. Stakeholders highlighted that the approach in the industry is more linear than circular, with a lack of consideration for the life cycle impacts. There is an impatience to achieve returns on investment and therefore a natural resistance to change from the manufacturers, builders, and higher management. However, large institutions have financial backing and the capacity to be drivers of change. As a part of their social and environmental responsibility, institutions can promote the implementation of less resource-intensive construction endeavors to create awareness by demonstrating its impacts.

The existence of hazardous substances such as lead and asbestos was cited as the greatest barrier to material reuse across all categories.

Environmental Barriers

The existence of hazardous substances such as lead and asbestos was cited as the greatest barrier to material reuse across all categories. All stakeholders conveyed their concerns regarding asbestos' presence in buildings to be demolished or deconstructed and consequently the presence of these hazardous substances in salvaged materials. The data available on the number of hazardous material abatements in Pittsburgh corroborates stakeholder perceptions as 723 active job sites have recorded the presence of asbestos, making a large quantity of these materials unfit for reuse. Currently, identifying alternative solutions for the management and disposal of asbestos-containing materials is essential in the context of Pittsburgh.

Sample Set of Non-Residential Deconstruction Projects in and near Pittsburgh (2010 - 2022)		
Project Name	**Owner / Deconstruction Implementation Agency**	**Presence of Hazardous Material On Site**
Former Homewood School, Demolition (2019) Pittsburgh, PA	Urban Redevelopment Authority, Landforce, Construction Junction	Yes
Transformazium (2010) *Braddock, PA*	Construction Junction	Unknown
Tri-COG Land Bank "Lead Safer" demolition - (2019) Millvale	Tri-Cog Land Bank	Yes
PNC Financial Services Group Headquarters (2012) Pittsburgh, PA	Construction Junction	Yes
Carnegie Mellon - Solar House (2018) *Pittsburgh, PA*	Construction Junction, Auberle, Landforce	No
UPMC Presbyterian South Tower (xx) *Pittsburgh, PA*	Construction Junction	Yes
Pittsburgh Botanical Gardens Barn (2018) *Oakdale, PA*	Construction Junction	Unknown
United Mine Workers simulated coal mine Creek, PA	Construction Junction, United Mine Workers of America, South Hilltop Men's Group	Unknown
Carnegie Mellon University - Scaife Hall – CMU (2019) Pittsburgh, PA	Construction Junction	Yes
University of Pittsburgh – Scaife Hall (2019-2020) Pittsburgh, PA	Landforce	Yes
Action Housing – Pgh Theological Apts - (2020) Pittsburgh, PA	Construction Junction, Landforce	Yes
Watson Institute - (2019) Sewickley, PA	Construction Junction	Unknown
St Basil's School (2019) Pittsburgh, PA	Construction Junction	Yes
St Basil's Rectory (2019) Pittsburgh, PA	Construction Junction	Yes
Philipsburg-Osceola Junior High School (2022), Pittsburgh, PA	NA	Yes
Carnegie Mellon University - Skibo Hall – CMU (2019) Pittsburgh, PA	Construction Junction	Yes
Note: 723 Active Job Sites In Pittsburgh Have Recorded The Presence Of Asbestos Till Date		

Figure 1.9: List of Deconstructed Projects with Hazardous Materials[17]

[17] Leturgey, E. (2022, November 14). Allegheny County Asbestos Permits. Western Pennsylvania Regional Data Center. Retrieved November 15, 2022, from https://data.wprdc.org/dataset/allegheny-county-asbestos-permit

It can also be noted that most deconstruction projects were administered by Construction Junction, bolstering the claim that the deconstruction industry in the city is niche. In a city, booming with construction there is great potential for developing a material bank and tapping into existing resources.

Political Barriers

The current regulations and policies surrounding sustainability and circularity have varied impacts on stakeholders. This leads to a difference in opinion on what is perceived as a barrier and whether it inhibits or promotes circularity. While most owners of institutions do not benefit from tax credits and other rewarding policies and regulations due to their nonprofit status, architects and contractors still could. The introduction of CE catalysts and initiatives for stakeholders along with the development of a policy-supported framework can incentivize stakeholders to implement these principles, as elaborated in Chapter 5. Additionally, the lack of certification and recertification of reuse materials deters stakeholders from employing them. An interview participant cited that materials procured through traditional methods such as wood have FSC certifications that ensure the quality and life of the product. However, such certifications are not available for salvaged or reused materials hindering their use. Amendments to policies and integration of certification programs for such materials could help promote the adoption of CE principles.

Organizational Barriers

Lack of support from top management and the lack of resource allocation for construction and demolition waste management were cited as the most significant organizational barriers to implementing CE in construction. As described by the interview participants both these barriers tie back to the lack of financing and economic limitations. The implementation of CE principles is seen as a cost and time-intensive venture as compared to demolition. Most projects are on a tight schedule and budget and view these changes to procedures as deterrents thus not garnering support from management.

Priority Chart

Figure 1.10 depicts the prioritized list of barriers from the various categories. The weightage assigned to each category along with the votes assigned to each barrier determined its position. The figure emphasizes that the most impactful barriers were technical or economic.It also highlights that while the environmental category was not stated to be very impactful, the existence of lead and asbestos on site is a grave concern in the context of Pittsburgh. This list can inform decision makers about the perceptions of stakeholders within the city and their concerns regarding the implementation of CE principles. The aim is to guide the development of more holistic frameworks to promote the adoption of circularity in construction.

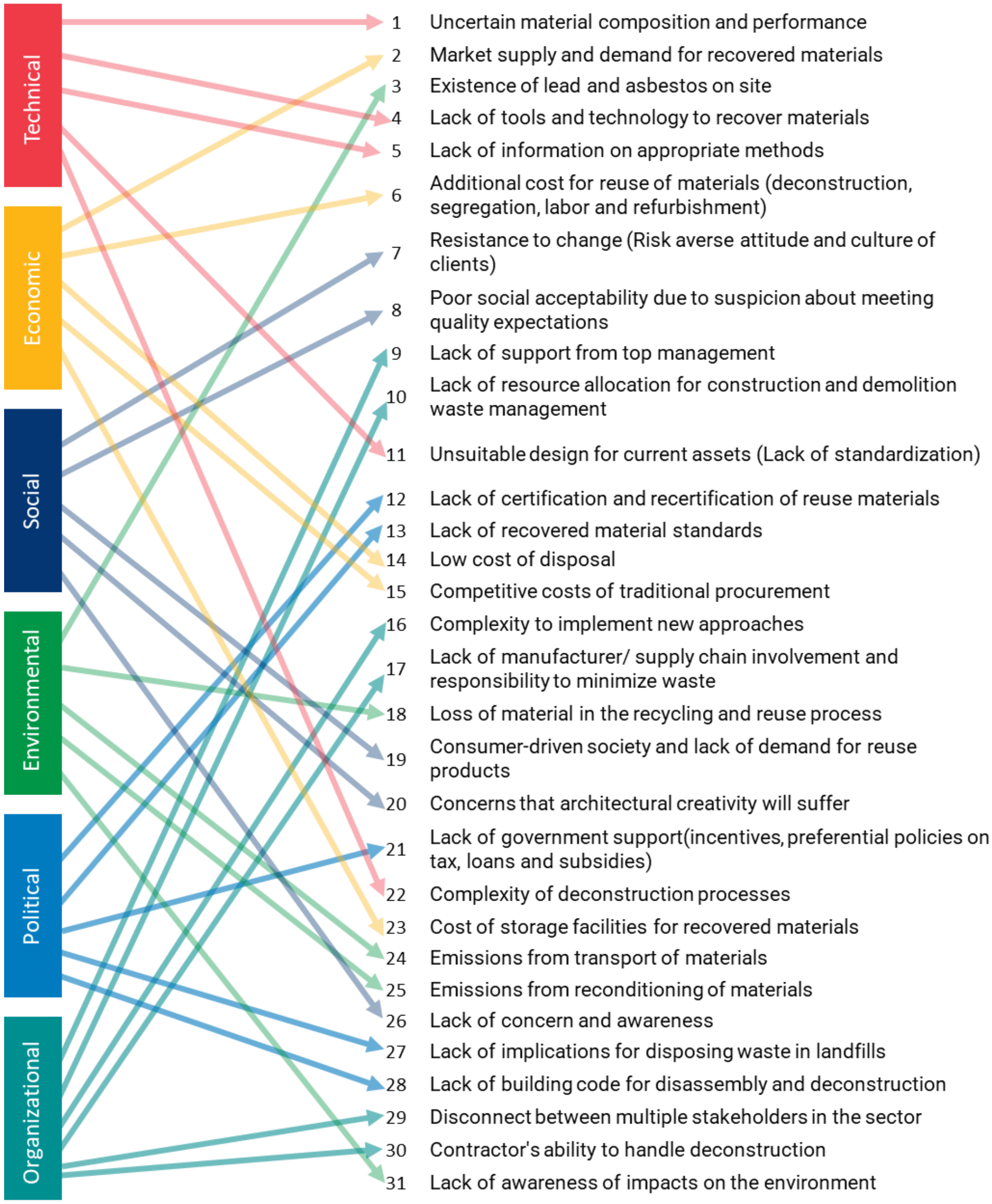

Figure 1.10: Prioritization of Weighted Barriers

Limitations

The study relies on clearly defined strategies collated through literature reviews of works by other authors.Therefore, the study does not account for other barriers that may be contextually relevant. The study was limited to 6 participants as a larger study would warrant an approval from the Institutional Review Board. This would lead to a prolonged study, beyond what can be achieved within a semester .Limitations on the number of participants may lead to inaccurate and presumptive outcomes, even though the number of participants within each category are uniform. The veracity of results can only be verified by further interviews. As such, the results are a guided opinion of what the outcomes of an extensive research could be. Results of this interview are also subjective and may be influenced by personal bias or external knowledge,beyond the domain established for this study. This can be noted through the analysis of responses within a stakeholder category wherein contradictory views drastically impact the weightage and votes of individual barriers. A comprehensive study with more participants could identify outliers and mitigate extreme results within the outcome.

Future Work

This research provides an insight into the perceptions and opinions on material reuse within the construction industry. However, conducting interviews with more participants would help in eliminating bias and highlighting nuances with individual stakeholder groups. This would also help in creating solutions that address key concerns and team goals based on the prioritized list of barriers. This study can also be used to identify tools and technologies that could be used by stakeholder groups to avoid and resolve concerns at various stages of the construction or deconstruction process. Some examples of tools that have a potential of mitigating these barriers include Building Information Modelling and Laser scanning to quantify materials and preempt composition and Life Cycle assessment tools as a decision making tool for identifying deconstruction strategies. The following chapters delve deep into the potential of these tools in this industry.

Eventually, the results of an expanded study can be compared against other project typologies within Pittsburgh and enable policymakers to develop toolkits that incentivize and educate organizations on material reuse. A consolidated list of barriers can also be used to influence business strategies of material reuse partners across the United States. Finally, the list of barriers can point to possible secondary markets as solutions that cannot be resolved by the construction industry itself. It could incentivize specific reuse businesses focused on project typologies, scales and even material composition.

CHAPTER 2- POTENTIAL DECONSTRUCTION STRATEGIES USING BIM TO ACHIEVE CIRCULAR ECONOMY AT CARNEGIE MELLON UNIVERSITY

AKHILA PENTRALA, POORNIMA KRISHNAN, TANNAZ AFSHAR

CHAPTER SUMMARY

Quantifying Construction and Demolition waste (C & D waste), and analyzing material reusability is critical for achieving a circular economy. While organizations have developed numerous frameworks for implementing a circular economy, there are limited studies analyzing the practical execution of this thinking, particularly in the higher education sector. Educational institutions strive towards developing a campus that is enduring and responsive to the dynamic future. They are critical aids in supporting sustainable development through teaching, research, and social outreach activities. Therefore, responsible resource consumption and controlled waste generation are essential to meeting their goals of sustainability.

This paper presented deconstruction strategies that Carnegie Mellon University can implement with the aid of technology to execute circular economy thinking in practice. First, background analysis and semi-structured interviews were conducted to determine Carnegie Mellon University's ongoing demolition and deconstruction practices and the limitations faced by the University's management and stakeholders in responding to these circular economy goals. This was followed by identifying a building slated to be demolished in the near future on campus and using Building Information Modelling as a tool to accurately quantify building materials. We further determined the feasibility of reusability of these materials to propose strategies for adopting a circular economic approach. Finally, an assessment of the outcomes was carried out to identify future research needs toward the implementation of a circular economy at Carnegie Mellon University. Our primary finding was that the university was involved with material recycling practices, with limited potential for reuse of architectural elements. Moreover, the building materials were currently not being assessed based on their "feasibility" for reuse or recycling, and a framework was developed for the same.

INTRODUCTION

Unsustainable resource consumption and climate change repercussions have significantly contributed to 60% degradation in the earth's ecosystem services over the last half-century. In the European Union (EU) alone, the construction industry accounts for 50% of raw material consumption, 42% of final energy use, and 35% of greenhouse gas emissions to generate 10% of the gross domestic product (GDP) per year. Hence, compared to the other industrial sectors, the construction sector is a voracious resource, energy consumer, and carbon producer.[18] Construction and demolition waste can be generated in the construction phase due to design errors, on-site mistakes, workflow confusion, unpredicted plant malfunctions, renovations, or during the end of the life cycle when the building service life is over. Waste source detection is the key to identifying waste outputs. Lockrey et al.[19] believed that an essential step in waste segmentation is a material classification which is an important knowledge limitation in the current environmental assessment methodologies. Pittsburgh is embarking on a transition to become a circular and sustainable city. Currently, from a C and D perspective in Pittsburgh total construction Inflow is approximately 145,000 tons/year and the total demolition outflow is approximately 81,000 tons/year which is almost 56% of the construction material inflow. Pittsburgh's zero waste roadmap for 2030 targets schools and universities to participate in their efforts to reduce waste generation.[20]

Currently Pittsburgh's total construction inflow is approximately 145,000 tons/year and the total demolition outflow is approximately 81,000 tons/year which is almost 56% of the construction material inflow.

To reduce the amount of waste going to landfills, a shift from a linear model to a more circular economy is required. Waste reduction and the circular economy would greatly benefit from deconstruction strategies to salvage materials from buildings that are nearing the end of their useful lives. Numerous studies have been conducted on the methods of waste management, which do not make use of technologies. These methods are often time-consuming and unreliable for quantifying waste.[21] In addition, adopting technologies such as BIM in a project's life cycle and generating material passports are useful for improving a material's potential reuse.

Higher education institutions must pay more attention to construction and demolition (C&D) waste management because campuses are known for producing a lot of waste.[22] Numerous theoretical frameworks have been developed for implementing a

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[18] Arghavan Akbarieh et al., "Bim-Based End-of-Lifecycle Decision Making and Digital Deconstruction: Literature Review," Sustainability 12, no. 7 (2020): p. 2670, https://doi.org/10.3390/su12072670.

[19] Simon Lockrey et al., "Concrete Recycling Life Cycle Flows and Performance from Construction and Demolition Waste in Hanoi," Journal of Cleaner Production 179 (2018): pp. 593-604, https://doi.org/10.1016/j.jclepro.2017.12.271.

[20] "Roadmap to Zero Waste - Pittsburgh," accessed December 14, 2022, https://apps.pittsburghpa.gov/redtail/images/543_Pittsburgh-Road-Map-to-Zero-Waste-Final.pdf

[21] Zezhou Wu et al., "Quantifying Construction and Demolition Waste: An Analytical Review," Waste Management 34, no. 9 (2014): pp. 1683-1692, https://doi.org/10.1016/j.wasman.2014.05.010.

[22] Joan Manuel Mendoza, Alejandro Gallego-Schmid, and Adisa Azapagic, "A Methodological Framework for the Implementation of Circular Economy Thinking in Higher Education Institutions: Towards Sustainable Campus Management," Journal of Cleaner Production 226 (2019): pp. 831-844, https://doi.org/10.1016/j.jclepro.2019.04.060.

circular economy (CE), but there are limited studies analyzing the practical execution of CE, particularly on university campuses. Carnegie Mellon University's (CMU) planning principles aim to achieve the United Nations' seventeen sustainability goals in addition to creating a timeless and enduring campus. Responsible resource consumption and waste generation in a controlled manner is essential in order to achieve this goal. Our project aimed to support CMU's sustainability goals by offering a framework to improve deconstruction by estimating reusable materials of a campus building using BIM and providing techniques to reuse them in subsequent projects rather than ending up in landfills.

Most studies that use BIM to evaluate a building's life cycle overlooked the facility's end-of-life stage

LITERATURE REVIEW

Circular economy (CE) in the construction industry has been an interesting topic for researchers. Applying CE principles into C & D waste management is a broad and complicated topic and it can be approached in several ways. Deconstruction is one strategy that shows promising outcomes in this regard. Our study addressed the gaps that we found in reviewing the previous research in each topic. The literature review was divided into three main topics of our study, deconstruction, BIM, and higher education institutions.

Deconstruction

Analyzing the deconstruction potential of buildings and the strategies to apply in order to reduce waste is widely being studied. Rios and Grau recommended Design for disassembly (DfD) to facilitate the future dismantling (or deconstruction) of the building with the ultimate purpose of facilitating the reuse of its components.[23] In addition, Bertino at el. proposed common principles for deconstruction as a sustainable alternative to demolition that can be applied during design and planning process regardless of material used.[24] While the majority of the structures that are being deconstructed were not intended to be disassembled, previous studies on deconstruction have mostly concentrated on the planning stage. In addition, most studies overlooked the particular materials used in buildings and strategies to reuse them in the future. As a result, there is a lack of research on the ability to deconstruct existing structures based on the particular building materials employed.

BIM

BIM as a tool is being used for newer constructions and material take-offs. Research has shown that with the support of concepts like design for deconstruction, BIM supports deconstruction for newer developments.[25] The adoption of BIM for older

[23] Fernanda Cruz Rios and David Grau, "Circular Economy in the Built Environment: Designing, Deconstructing, and Leasing Reusable Products," *Encyclopedia of Renewable and Sustainable Materials*, 2020, pp. 338-343, https://doi.org/10.1016/b978-0-12-803581-8.11494-8.
[24] Gaetano Bertino et al., "Fundamentals of Building Deconstruction as a Circular Economy Strategy for the Reuse of Construction Materials," *Applied Sciences* 11, no. 3 (2021): p. 939, https://doi.org/10.3390/app11030939.
[25] Olugbenga O. Akinade et al., "BIM-Based Deconstruction Tool: Towards Essential Functionalities," International Journal of Sustainable Built Environment 6, no. 1 (2017): pp. 260-271, https://doi.org/10.1016/j.ijsbe.2017.01.002.

structures which has a lot of scope to be further researched on has not been explored. In the current day, BIM is utilized for planning and execution purposes. A growing number of studies that use BIM to evaluate a building's life cycle overlooked the facility's end-of-life stage, where demolition happens.[26] Our research focused on using BIM as a tool to help in material quantity take-offs of the existing structures' deconstruction rather than the construction of new ones.

Higher Education Institutions

The development of activities to enhance the circular economy has begun at many higher education institutions. Studies on initiatives aimed at increasing sustainability and frameworks for applying CE principles to the higher education sector have been done in regions such as Europe and Australia (such as James Cook University (JCU) and University of the Sunshine Coast(USC)).[27] In his research, Mendoza proposed and applied a CE framework to the case of the University of Manchester in order to increase resource efficiency and environmental sustainability of campus operations[28]. The city of Pittsburgh is moving from a linear model for economy to a circular economy. Despite having sustainable practices and C&D waste management, Carnegie Mellon University (CMU) has not developed a CE framework for prospective solutions to improve such activities. Our analysis highlighted CMU's present practices and offered recommendations to enhance CE on campus to solve this gap.

PROBLEM STATEMENT & RESEARCH QUESTIONS

As noted above, previous research has corroborated that BIM has strengthened the construction industry with significant benefits to the project lifecycle. Furthermore, it is a shared knowledge resource for information about the facility forming a reliable basis for decisions during a building's life cycle right from its inception. However, while BIM has been implemented in the construction process, limited data or studies have been conducted with regard to its use in deconstruction. Inefficient traditional methods of quantifying C&D waste are being used. Many barriers have been identified with the use of BIM in current practice, impacting stakeholder decision-making and project efficiency.

Similar to construction, deconstruction involves the objectives and interests of different stakeholders. However, it has not been considered as a project planning criterion for deconstruction projects. An area of particular interest for exploration is understanding sustainable development in the higher education sector. While studies have been conducted to help universities develop a methodological framework aimed at

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[26] Lovelin Obi et al., "Bim for Deconstruction: An Interpretive Structural Model of Factors Influencing Implementation," Buildings 11, no. 6 (2021): p. 227, https://doi.org/10.3390/buildings11060227.
[27] Katja Fleischmann, "Design-Led Innovation and Circular Economy Practices in Regional Queensland," *Local Economy: The Journal of the Local Economy Policy Unit* 34, no. 4 (2019): pp. 382-402, https://doi.org/10.1177/0269094219854679.
[28] Joan Manuel Mendoza, Alejandro Gallego-Schmid, and Adisa Azapagic, "A Methodological Framework for the Implementation of Circular Economy Thinking in Higher Education Institutions: Towards Sustainable Campus Management," *Journal of Cleaner Production* 226 (2019): pp. 831-844, https://doi.org/10.1016/j.jclepro.2019.04.060.

achieving CE in other countries, a local study in the context of Pittsburgh has not been developed.

Based on the recently published 2022 master plan of Carnegie Mellon University indicating buildings to be repurposed in the near future, and an analysis of their current demolition strategies, we arrived at the following question that established our research:

How can potential deconstruction strategies be implemented at Carnegie Mellon University, with the use of technology, taking a dormitory building slated to be demolished as a case study, to maximize resource efficiency?

METHODOLOGY

The research study employed a mixed methods approach that combines semi-structured interviews, evaluative site studies using Building Information Modeling, and relevant case studies to answer our research question. This approach offered flexibility, and provided detailed qualitative data to validate the insights provided by quantitative data. The interviews helped in analyzing the current demolition strategies implemented by different stakeholders at Carnegie Mellon University, while employing a combination of Building Information Modeling and relevant case studies to propose better strategies for a Circular Economy.

Method 1 - Semi-Structured Interview

The first phase of the research included semi-structured interviews with stakeholders of the two demolished buildings identified at the Carnegie Mellon University campus, to understand the process of demolishment undertaken, and how the different materials identified were segregated and treated. The university's collaboration with non-profit material resellers was identified to determine the percentage of waste being set aside for reused/recycled and diverted to landfills. Furthermore, interviews with different stakeholders involved in these projects provided insights into the process of how they managed C & D waste. The recruitment of participants was based on their degree of involvement with the two demolished buildings identified, their experience in the industry, and their educational background. The interview recordings were transcribed into text for further analysis by the authors afterward.

Method 2 - Reconstructed 3D Model and BIM

Accurately estimating building materials and developing a framework for efficient waste management practices at the university was done by utilizing BIM. This model was constructed based on the building's floor plans that were procured from the CMU archives, data collected by images, and interviews of stakeholders to understand the type of building materials and their location. Employing BIM as a tool helps managers understand the location of materials and consequently identify areas of deconstruction. The modeling work involved three tasks: 1) modeling geometry information of building components, 2) assigning a BIM object category (door, wall, etc.) to a component, and 3) establishing relationships between components. The creation of a BIM model was particularly helpful in documenting an old building. Once the framework was constructed, identifying the location of different types of materials, accurate quantity take-offs and total waste volumes could be computed. Furthermore, BIM was a useful tool to estimate the amount of demolition waste, disposal charge fees, and the costs of logistics. The quantity of each type of building material was extracted from the as-built BIM by material types and building levels. The measurements were classified as numbers (e.g., the number of doors or windows) and volume (cubic meters).

Method 3 - Case Studies

Case study explorations helped suggest strategies for adopting a circular approach circular economic strategy at the University. As part of this phase of the study, relevant case studies across campuses in different countries, like the universities in Netherlands and Singapore, were identified on the basis of waste classification and viability of materials for reuse, stakeholder policies, and urban-mining strategies to understand the tools and techniques employed in these countries towards achieving a circular economy. The relevance of these studies in the context of Pittsburgh was identified based on the analysis conducted on prior interviews to understand the current practices. Factors influencing the reuse potential of reclaimed materials were identified based on the following characteristics: availability, ease of detachment, ease of refurbishment, and reuse potential. Furthermore, case studies were particularly useful for critical analysis of existing theory as well as understanding unique or emerging events where there was little knowledge available about a complex phenomenon.

FINDINGS

Background Information

Carnegie Mellon University was founded in early 1900's as the "Carnegie Technical Schools", serving young men and women in the Pittsburgh region, and became a degree-granting institute in 1912. In 1967, the Carnegie Tech merged with "Mellon tech", and has since soared to national and international fame. The university has been striving to meet Pittsburgh's zero waste roadmap of 2030 that targeted schools and universities to participate in their efforts towards reduced waste generation. Building on that, this study is focused on providing strategies for limiting Construction and Demolition waste for the university.

The university's institutional master plan provides an action plan for the future development of the campus, conforming to the institution's sustainable vision for the future. Carnegie Mellon's planning principles sought to achieve the United Nation's seventeen sustainability goals besides creating a campus that is "timeless", and "enduring". Their primary agenda was to control waste generation and consume resources responsibly. While numerous studies have been established in developing a theoretical framework towards implementing a circular economy, no practical execution of the same has been analyzed.

From the 2012-2022 Campus Development Master Plan, it could be observed that there was a lot of scope for demolition and rebuilding in the near feature. As shown in the image below, it was noted that the buildings falling into the blue dotted zone were a part of the historic core, and were aimed to be worked on first. The opportunities of expansion in the historic core were mostly limited to additions and reuse of existing buildings, preserving the university's iconic buildings and views. With our study's goal of limiting construction and demolition waste, a framework for the study was developed based on the analysis of the university's current demolition process.

Figure 2.1: Carnegie Mellon University 2012- 2022 Campus Development Masterplan

From the image above, it can be observed that the buildings highlighted in purple are the projects that were already demolished, and are currently under construction, while the buildings highlighted in red are the projects that are slated to be demolished in the next five years. The 120,000 sf Scaife Hall was chosen as the recently demolished building our study would cover, and Donner house was chosen as the building for the phase 2 of our study that entailed constructing a BIM model and proposing reuse strategies. This analysis established the framework of our study, the findings for which would be covered in the subsequent sections.

Phase 1: Scaife Hall Demolition

Scaife hall opened in 1962 on the campus of the College of Engineering, serving as the home of the mechanical engineering department for nearly six decades. The design of the original Scaife hall offered state of the art research labs, office spaces and technology, thereby elevating the department and university. In 2020, the old Scaife Hall at CMU was demolished, thus becoming an ideal resource for collecting data regarding the demolition process. As mentioned in the research methodology section, semi-structured interviews were conducted with stakeholders involved in the demolition process to understand the process of demolition undertaken, the segregation and treatment of materials, and the University's present-day collaboration efforts with non-profits, the details of which are provided in this section.

Asbestos abatement led to a delay in the demolition process

The demolition process began in October 2020 and underwent multiple phases. The Phase 1 of the process: asbestos abatement was carried out from Late Aug 2020 - Mid November 2020. The Phase 2 of Interior Selective Demolition was carried out for a month starting Early October 2020. The final Phase of full demolition started Mid-November 2020, and proceeded for 3 months. A critical issue highlighted in the demolition process was asbestos abatement that led to a delay in the demolition process. A majority of the old buildings across the University campus face this issue, as a consequence of the use of asbestos in a variety of building construction materials in the early 1900's.

Carnegie Mellon University funded the demolition process, while Campus Design and Facility Development oversaw the process as the owner's representative. PJ Dick-Trumbull-Lindy Paving served as the General contractor on the project and hired Noralco Corporation as a subcontractor for the demolition work. The budget for the demolition work was $223,000. On speaking to the General contractor involved in the project, it was observed that most structural materials involved in the project were sent for recycling. The site logistics were planned to segregate and store construction waste that were periodically removed. The General contractor sent across the ferrous and non-ferrous scrap to American Steel Processing, Wood debris to Elkun Industries, while Non-Ferrous scrap was sent to AAA Scrap metal. Moreover, it was observed that there were categories such as miscellaneous and C&D debris that did not categorically specify the materials that were sent for recycling.

Table 2.1: Monthly C&D Waste Summary in Net Tons

ITEM	DECEMBER 2020		JANUARY 2021	
	RECYCLED	LANDFILL	RECYCLED	LANDFILL
Structural Steel	132.83		166.45	
Rebar	7.69		-	
Light Gauge Steel	-		0.62	
Masonry	-		-	
Concrete	-		-	
Miscellaneous	-		-	
Construction and Demolition Debris		105.12		
Aluminium	10.25		17.27	
Copper	-		-	
Stainless Steel	-		-	
Press	92.43		159.47	
Totals	243.4	105.12	343.81	

Another observation was that Carnegie Mellon University closely collaborates with construction junction, Doors Unhinged and Habitat for humanity by donating furniture, doors, windows and used appliances for salvage and reuse. For Scaife Hall specifically, building components and some furniture were donated to the Mechanical Engineering Department for reuse. All other materials segregated on site were sent for recycling. It can be observed that the reuse potential of these materials were not assessed, and hence the possibility of reusing architectural elements were limited.

Table 2.2: Material Type and Salvage Method

ITEM	MATERIAL TYPE	MATERIAL STREAM	TOTAL WASTE (TONS)
Doors Unhinged Salvage	Other (Specify)	Donated	10.80
Construction and Demolition Debris	Other (Specify)	Landfill Waste	105.12
Demolition - Structural Steel	Metals	Recycled - Source Separated	299.28
Demolition - Rebar and Light Gauge Steel	Metals	Recycled - Source Separated	8.31
Demolition - Aluminium	Metals	Recycled - Source Separated	27.52
Demolition - Press Metal	Metals	Recycled - Source Separated	252.10
Construction	Commingled Waste	Commingled - Recycled	1.83

Looking at the segregation categories such as construction and demolition debris, it is not possible to know what exactly went into the process of demolition and what materials were actually sent to the landfill. That is why the integration of BIM into the deconstruction process helps pinpoint each material with their exact quantity, which can help optimize the whole process.

Phase 2: Donner House Site Visit and BIM Model

Donner House was designed in 1954 to by Mitchell and Ritchey clad in Roman-bond green-glazed bricks as a sign of American modernity. It was designed as a freshman residential building on campus and is three stories tall. The building has undergone multiple renovations since the 1950s and is a part of the historic core of the campus. The building is slated to be demolished in the next five years, and hence was a suitable candidate for research.

Figure2.2: Donner House

The data collected from building inception to demolition could be used to tackle waste, both during construction and the end-of-life (EOL) of the building.[2] For the purpose of Sustainable end-life management, seven new BIM uses were identified: Digital Model for End-of-life, Material Passport Development, Project Database, Data Verification, Circularity Assessment, Material Recovery Processes and Material Bank. As part of this research, an end-life Revit model was developed to quantify building materials, and analyze the quality and quantity available. Material passports were further developed followed by a circularity assessment to gauge the reuse and recycle potential of all building materials.

For the purpose of this study, floor plans and building details were procured from the University's archives for analysis. Since the building had been renovated over the years since its inception, a tour of the building was conducted to analyze the new renovations, and gauge the present-day quality of materials. The two sources mentioned above were critical aids in developing the Revit Model that was developed by modeling the geometry information of all the building components, and assigning appropriate materials. This was useful in documenting the old building, and developing material passports for further analysis.

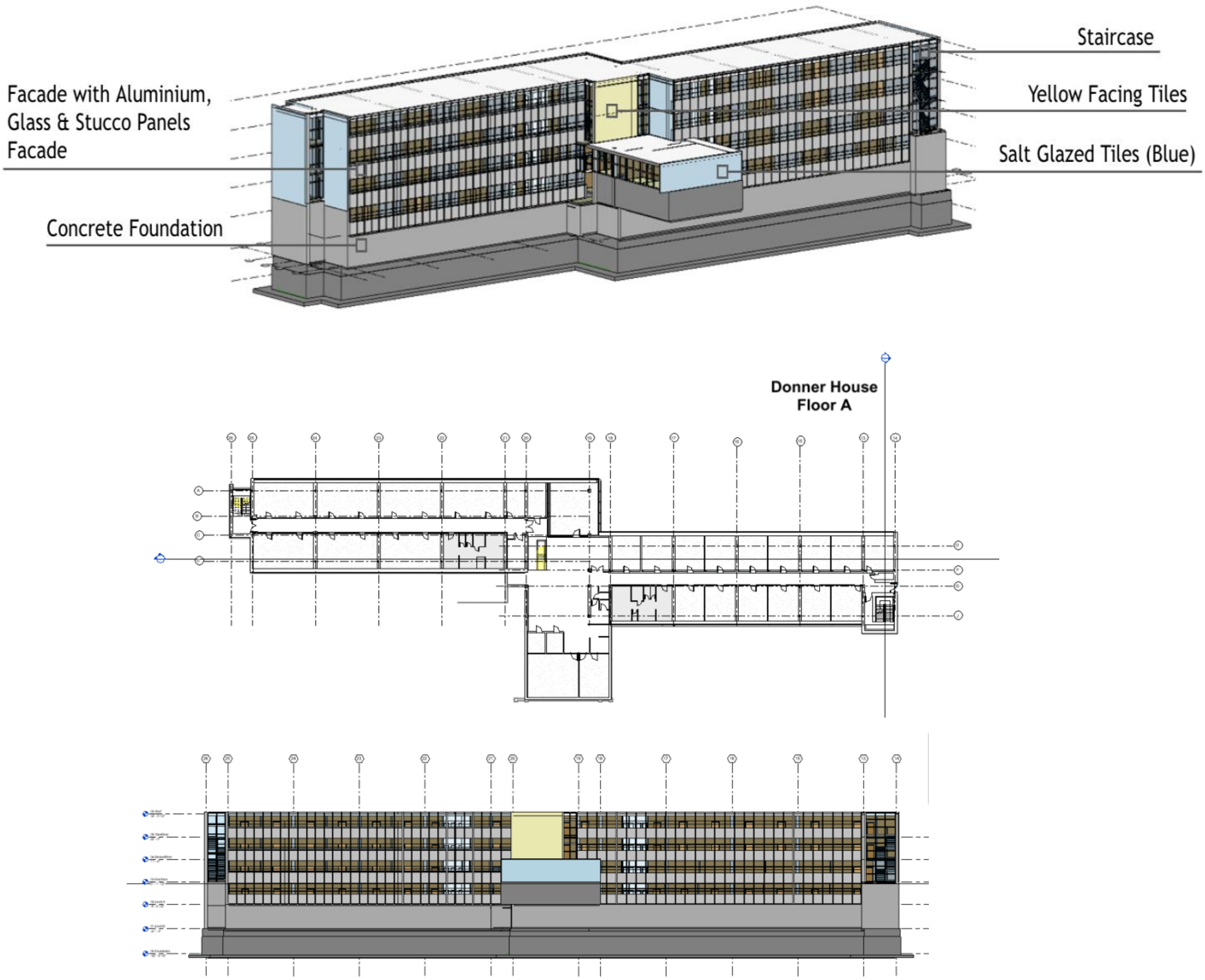

Figure 2.3: BIM model developed using Donner House Plans Identifying Different Building Components

The use of Building Information Modelling in documenting the building was critical to gain an accurate understanding of the building, and its components. On conducting interviews, stakeholders expressed apprehension towards adopting technology due to a limited budget, lack of knowledge of the technology, and the enormous time that went into developing these models. However, the precision that these models offered particularly towards decision-making was unparalleled. Since deconstruction is laborious, an analysis and pre-established model of the building could facilitate faster and accurate work. The materials found and quantified were used for further analysis as discussed in the subsequent section.

Stakeholders expressed apprehension towards adopting technology due to a limited budget, lack of knowledge of the technology, and the enormous time that went into developing these models

Phase 3: Feasibility of Materials for Reuse Potential

With the University's objective of meeting the seventeen sustainable development goals proposed by the United Nations, and its aim to achieve a campus that is enduring, it was important to propose strategies for a modern, resource-efficient and sustainable community that is resilient. [1] Within the scope of this research, the impact and reuse/recycle potential of materials were studied through the lens of Urban Mining. This tool could help move from a linear economy to a circular economy, where 'waste' becomes a resource, thereby reducing the need for newly mined materials. With construction industry being one of the largest industries that consumes natural resources, it was important to adopt working practices that enable the reuse of architectural elements. Deconstruction as a practice is critical to closing material flows, further complying with the process of circularity within construction. For materials to be reused, "Feasibility" as a factor needed to be considered in order to gauge the feasibility of harvesting existing materials.

The characteristics that determine the viability of reuse are listed as follows: Availability, Ease of Detachment, Ease of Refurbishment, Reuse and Recycle Potential. "Availability" pertains to the quality and quantity of a certain material at a building site. The preference would typically be to procure a large quantity of materials from the same location because of the logistical and financial benefits it offered. Since deconstruction is already a complex process, the ease of procuring a significant quantity of material from a single construction site would be favorably welcomed by building contractors.

"Ease of detachment" refers to the way the building was originally constructed, the systems employed, its documentation, and the availability of relevant information present. Moreover, it takes into consideration the transportation and storage possibilities of salvaged material, thereby suggesting the benefits of harvesting from one single location. Looking at the table below, it can be observed that materials such as steel with bolted joinery would be far easier to disassemble, in contrast to cast-in-situ concrete. Especially since Donner house was constructed in the 1950's, it was very critical to understand the viability and application of construction materials in present day.

The third and fourth characteristics' ease of refurbishment' and 'reuse potential' are closely related to each other, thereby referring to the effort that needs to be taken to make a material or component ready for reuse. The more effort required to refurbish a material makes it less favorable for reuse. For instance, the salt glazed tile were cement mortared to the concrete block, thereby deeming it impossible to efficiently remove the building material from the blocks. This in turn reduced the potential for reuse since it had to be panelized as a unit along with the concrete block.

Table 2.3: Donner House Material Viability Chart

Viability							
Material Name	**Type of Joinery**	**Availability**	**Ease of detachment**	**Recycle Potential**	**Re-use Potential**	**Ease of refurbishment**	**Material Quantity**
Building Structural System							
Steel Beams and columns	Bolted Joinery	Positive	Positive	Positive	Positive	Intermediate	3290.84 CF
Concrete Foundation	Cast In-Situ	Intermediate	Negative	Positive	Negative	Negative	23569.14 CF
Walls							
Concrete Blocks	Cement Mortar	Positive	Intermediate	Positive	Intermediate	Intermediate	69181.98 CF
Drywall - Studs, paneling & Insulation	Nailing	Intermediate	Intermediate	Positive	Intermediate	Negative	5559.84 SF
Facade							
Salt glazed tiles(Blue)	Cement Mortar	Negative	Intermediate	Negative	Positive	Intermediate	4634.01 SF
Facing tiles(Yellow)	Cement Mortar	Negative	Intermediate	Negative	Positive	Intermediate	539.77 SF
Aluminum frame, stucco panels and glass inserts	Assembled on site	Intermediate	Positive	Negative	Intermediate	Positive	1310.65 CF
Floor slab	Reinforced Concrete Slab	Intermediate	Negative	Positive	Negative	Negative	67337.58 SF
Doors and Window	Assembled on site	Positive	Positive	Intermediate	Negative	Positive	244 doors 768 windows
Staircases	Assembled on site	Intermediate	Positive	Positive	Positive	Positive	10
Internal furniture		Positive	Positive	Negative	Intermediate	Positive	

Positive Intermediate Negative

The reuse potential, on the other hand, refers to "multiple" possibilities of a material or component to be reused. Recycle potential, on the other hand, refers to reconfiguring materials for use again. These two factors were considered to gauge the percentage of materials that could still be reused with minimal intervention.

With all the material inventory generated using BIM, the creation of the Viability chart helped generating a log of all the available material. Overlapping it with a scale of green as positive, yellow as intermediate and red as negative was essential in easily scoring materials based on the ease of detachment, recycle potential, reuse potential and ease of refurbishment. Positive here refers to an affirmative of a specific category, for instance, positive availability here refers to an abundance of high-quality material. Negative, on the other hand, refers to the lack of material availability or difficulty of detachment and refurbishment. The building was segregated into seven major categories as follows: the building structural system, exterior walls, interior partitions, facade, doors and windows, staircases and internal furniture.

The skeleton of the building was made up of steel beams and columns (3290.84 CF) which lay on top of a concrete in-situ raft foundation. The material with its bolted connection was rated positive, since it could be easily disassembled, with less wastage involved in the process. The reuse potential of steel is limited as it faces significant logistical barriers that could be attributed to insufficient storage, lack of knowledge on the material's property cost of effective storage and cataloging. However, with proper treatment, the procured steel could be applied in another sector altogether like agriculture, or used in warehouses as bracing and base plates. Furthermore, the material could be used as temporary work systems such as formwork and scaffolding on the University's campus. While reuse offers greater environmental advantage, building stakeholders are more amenable to recycle. Another possibility with

> The reuse potential of steel is limited as it faces significant logistical barriers that could be attributed to insufficient storage, lack of knowledge on the material's properties, cost of effective storage, and cataloging.

regards to recycling was that the materials could be completely melted and recycled into another component or a new structural member all together.

With the presence of metal rebars in the concrete foundation (32569 CF), it was tough to be detached and segregated. A viable proposal would be to retain the foundation as is, and design a structure that would conform to the structural grid of Donner house. In a scenario, that this is deemed impossible, the alternative of employing a “Smartcrusher” could be employed. The device is used to grind concrete pieces down to a powder form, and could be recycled with the help of some additives into a new material altogether. Currently, there are other alternatives such as slab sawing, which employs heavy machinery to break the structure down into standardized sizes. These could be further panelized and used elsewhere in a new construction.

The exterior walls of the building along with a few interior elements are made up of concrete blocks which have been joined using cement mortar. Furthermore, the exterior blocks had green salt-glazed tiles which were also cement mortared to the concrete blocks. The use of cement mortar was restrictive in flexibly altering the building’s reuse potential. An alternative to this was panelizing all the walls and reusing it elsewhere as a new construction. These panelized concrete blocks could also be used as landscape elements on campus such as planter boxes. From a design standpoint, using the panelized construction as an interior wall with minimum aesthetic requirement would be recommended. Another possibility would be to break down these tiles and use them as mosaic on campus. In a scenario such as this, the concrete blocks could be ground down by the smart crusher for later reuse.

The interior drywalls were made up of wooden studs cladded with gypsum board. All these components were nailed together, and hence is a time consuming process to segregate them. If performed efficiently, the wooden studs could be reused for interior walls in new buildings, and the gypsum boards could be trimmed, resized and used again. If the panels were to break, they could be crushed and used for soil amendment. Another alternative would be to panelize the drywall as a whole, and reuse it. This could unfortunately take up a significant amount of storage space.

The facade was made up of an aluminum frame system with glass inserts and stucco panels. These could be easily dismantled and used in a new project with minimal refurbishment. Standalone aluminium frames could be reused as abstract light fixtures on campus or be reused as sculptural elements. Moreover, they could be reused as partition walls and integrated into the interiors of any campus building. Furthermore, The stucco panels could be used as a replacement to gypsum board in new constructions as it has high structural integrity.

The prefabricated steel staircase (10 in number) could be easily disassembled and used as individual components across buildings on campus or used on another construction project as a temporary work system for new construction or demolition projects.

The interior wooden doors of varying design types and aluminum framed windows could be easily dismantled and donated to organizations such as construction junction, doors unhinged and Habitat for Humanity for refurbishment and reuse. With adequate storage space for these in these organizations, they could be categorized based on size and material. While there is technology availability for adapting door types, technology to transform one door type to another is currently limited. This poses a major challenge since the size of doors and windows of buildings constructed in the early 1950’s do not meet the standards of today, and hence are unable to be largely adapted for reuse.

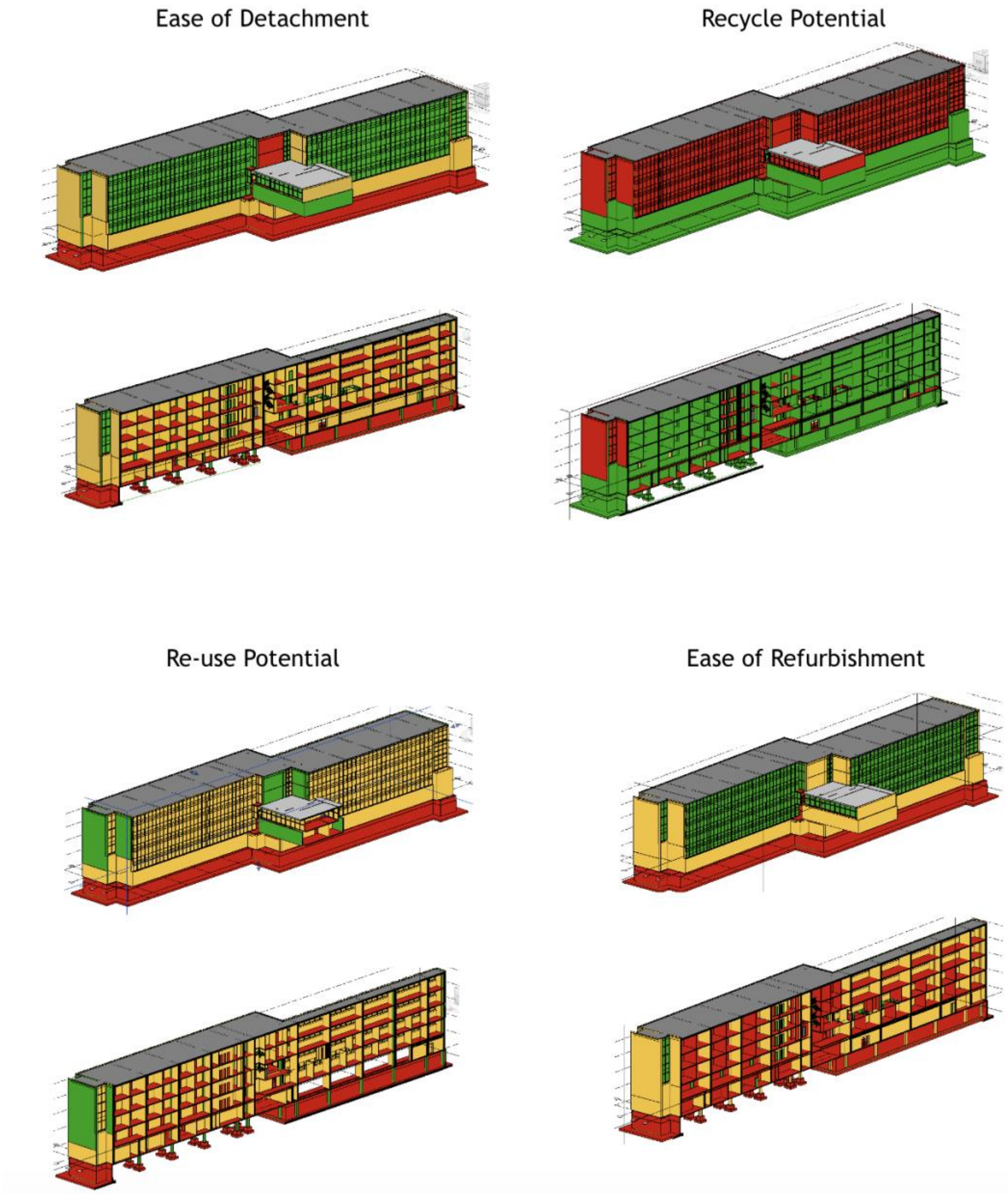

Figure 2.4: Revit model reflecting the different Material Viability Parameters

DISCUSSION

With the construction industry being the largest consumer of natural resources, there is increasing pressure to adopt working practices that enable the reuse or recycling of building materials. This demands an alternative that strives to maximize the use of recovered materials and closing material flows. This study provides a practical framework of implementation to realistically assess the effectiveness of employing technology for quantification, particularly for higher education sectors. Higher education institutions represent an area of particular interest to circular economy due to their socio-economic relevance and influential role in supporting sustainable development.

The findings above denote that Carnegie Mellon University is not fully equipped with circular economy operations due to a lack of apprehension in its adoption from stakeholders, financial and time constraints.

The use of BIM and other technologies could optimize estimation methods and make them far more accurate. Depending on the building typology, procedural strategies of employing technology would change, but the baseline method for the procedure would still remain the same. While initial first cost investment in BIM technology would increase the project's cost, it would be beneficial at later stages. BIM also helps in better stakeholder engagement, by making it easy for them to study every stage of the building lifecycle in a detailed manner and plan the deconstruction process more effectively.

> The use of BIM and other technologies could optimize estimation methods and make them far more accurate

There are multiple interventions needed at the Carnegie Mellon University campus to redevelop into a fully circular and energy efficient institution. An inventory of the materials present in the Donner House was prepared and its reuse potential was evaluated. Based on the analysis, materials were listed with some materials such as concrete, steel and wood having large financial value for reuse. Moreover, implementation of new technology to recycle materials could prove to be financially heavy in the beginning but can pay back at a later period. Moreover, a topic such as circular economy must not be assessed only from a financial perspective but must also take into account the environmental and health benefits it could provide in the long run. Creating an urban mining framework on the University's campus address three aspects of the value chain: supply, demand and connecting the two at a small-scale level. In order to facilitate this, a range of policy options and a framework for urban mining would have to be developed.

Recommendations

The following recommendations are provided in order to effectively employ circular economy in institutions:

- Policies to incentivize the practice of circular economy with a token of recognition for stakeholders partaking in its practice.
- Prioritize reuse over recycling and encourage the campus to identify more non-profits such as Construction Junction to send across materials with reuse potential.
- Integrate the use of BIM and laser scanning at the university level, to accurately determine materials and their quantities for future reuse.
- Prepare a framework for executing urban mining strategies within campus and achieve the target of carbon-neutral campus by 2030.
- Prioritize materials based on their "feasibility assessment" and provide storage facilities on campus for future reuse.
- Propose design strategies that incorporate "design for deconstruction" at the nascent stage of a project, to make deconstruction a successful practice of the future.

Limitations

The research was limited in several important ways. Firstly, all interviews conducted were a reflection of a specific individual based on their experiences, and may not be an accurate account of a specific topic. Secondly, the presence of asbestos in the building severely limited the reuse potential of many materials, and this would add significantly to deconstruction practices that are already expensive. The presence of asbestos presents yet another problem as it may make it difficult to estimate waste quantities accurately until deconstruction is underway. Similarly, not all of the building's potentially reusable materials can be salvaged, and some waste is unavoidable as the structure is being taken down.

Finally, since the Donner House building was constructed in the 1950s The drawings used as references to create the BIM model were very old and difficult to comprehend. As a result, there was little knowledge of the building's specifications. In addition, during the site visit, it was observed that some renovations had occurred, that were not easily quantifiable.

Future Work

The use of automated software and equipment in deconstruction could benefit from additional research and implementation. It is necessary to create an as-is model to get the most accurate results. This is especially helpful for historic buildings without available blueprints or for buildings that have undergone renovations and modifications and the current state doesn't match the original drawings. In future research other data acquisition techniques such as LiDAR should be tested to understand the and compare the outcome. Furthermore, more research is needed on the subject of material quantities of existing building to achieve a factor for percentage of waste in deconstruction projects.

For each of the building materials, the environmental and financial feasibility were not considered within the scope of this study. These would impact the analysis of each of the building materials since only a portion of the feasibility assessment was carried out as part of this study. It is also important to sudy the use of BIM and other emerging technologies as part of the project lifecycle right from design development all the way through to execution.

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CHAPTER 3- RIVETED, BOLTED, OR WELDED? A REUSE POTENTIAL COMPARISON OF STEEL CONNECTIONS IN THE STEEL CITY

JOHNS THOMAS VELLIKARA, MEGAN CAMPBELL, POOJITA KODALI, VAIBHAVI SHAH

CHAPTER SUMMARY

Pittsburgh, also commonly referred to as the Steel City due to its rich history in the steel manufacturing industry, now has many abandoned low rise exposed steel mill buildings around the region that are being demolished. Fortunately, most of the steel from these buildings is being recycled, but recycling of steel is a highly energy intensive process and hence not the best option. Instead, reusing these steel members through an adaptive reuse of these steel structures may save considerable energy as well as increase jobs in the steel construction industry. As designers it is essential that design decisions which affect deconstruction and reuse potential of the old or new steel structures are carefully considered. Through our research we therefore aim to analyze which steel connection type - bolted, welded, riveted has benefits over the others in terms of cost and time for construction and deconstruction and the maximum material salvage potential.The research was phased in three parts. Case study of a reused steel mill in Pittsburgh (Mill-19). Estimation of the cost, time, and material salvaged for construction and deconstruction of welded, bolted, and riveted steel connections using a prototype model and RS Means. Visual simulation study on a prototype model using Revit, and Navisworks to outline the time taken for each connection type.

- The case study showed that steel from 70-80 year old steel buildings can be used for both structural and non-structural purposes in a new construction after positive strength and inspection tests.
- The simulation study showed that based on construction and deconstruction cost, bolted structures are the most economical option.
- Welded and riveted structures are 21.78% and 36.59% more expensive to construct than bolted structures and take 8.3% and 62.02% more time respectively.
- For deconstruction, while riveted and welded structures take double the cost i.e are 100% more expensive than bolted structures they take up to 25% less time. Hence if time is the priority they can be better options.

- The material salvaged for bolted structures post deconstruction is found to be the maximum at 100%, followed by welded structures at 98.24% and riveted structures at 95.6%.
- The main cost and time intensive steps seen during the construction study were the third party inspection of welds in Pittsburgh.
- Bolted structures lose their advantage over the other connections if the bolts are rusted and the reusing of steel requires filling the holes

To increase feasibility of reusing steel, it is essential that the storage and handling units are close to the project site as it helps reduce cost on logistics. It is also important that the reusing of material reverses the design process, i.e instead of material ordered based on the design, here the design has to be made out of the available material members and sizes. This ensures that hauling is minimized and the supply chain on the project site is not disrupted as well making the reuse easier. Policies on recertification models for reuse of steel can be studied from other parts of the world to make the process easier in the US, incentivizing and encouraging the reuse of steel over recycling.

INTRODUCTION

Steel has a deep-rooted history within Pittsburgh, and played a large role in the industrial movement and economic prosperity of the area. The steel industry in Pittsburgh began in the 1800s following the lucrative iron industry that was introduced during colonial America. As the demand for iron increased between 1840 and 1870, deforestation became a large problem as a result of coal mining. With the introduction of cheap coal and coke (pure carbon created through the burning of coal in the absence of direct contact with air) to the industrial process helped to pave the way for the steel industry to rise. By 1879, there were a total of eight Blast furnaces producing steel, and 34 rolling mills to fabricate the steel within Pittsburgh. Following a decline in steel production, around the mid 1980s, 75% of the steel production facilities within Pittsburgh were "shuttered" or closed down.[1] Due to the historical impact of the steel industry and the many steel structures within the city, Pittsburgh makes a great location for introducing circular economic principles and deconstructable steel structures within the building sector.

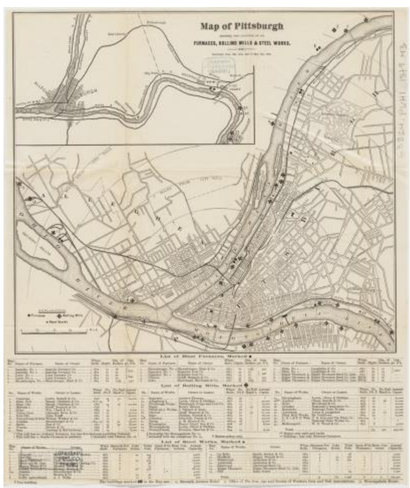
A main component of constructing and deconstructing steel structures are the structural iron and steel workers who are tasked with erecting, placing, and joining the steel columns, girders, trusses, etc. that form the structural framework. While structural iron and steel workers are known as "erectors" they can also play an important role in the "demolition, decommissioning and rehabilitation"[2] of older building structures. In 2021, structural iron and steel workers held around 69,000 jobs with 1,780 employed in Pennsylvania.[3] The largest employers of structural iron and steel workers are foundation, structure, and building exterior contractors (which made up 48% of projects), and nonresidential building construction (which made up 19% of projects). The location

[1] Dietrich III, William. "A very short history of Pittsburgh." Pittsburgh Quarterly. August 25, 2008. https://pittsburghquarterly.com/articles/a-very-brief-history-of-pittsburgh/
[2] U.S. Bureau of Labor Statistics. "Ironworkers" https://www.bls.gov/ooh/construction-and-extraction/structural-iron-and-steel-workers.htm#tab-1
[3] U.S. Bureau of Labor Statistics. "Ironworkers" https://www.bls.gov/ooh/construction-and-extraction/structural-iron-and-steel-workers.htm#tab-1

quotient defines the area's distribution of employment in reference to the area's distribution of work available, given Pennsylvania's location quotient of 0.66 the state has a higher employment compared to the work available and highlights the need for this sector to expand its scope in order to fit the needs of the area.[4] This makes steel a profitable and important material in the context of Pittsburgh, Pennsylvania.

Finally, it is important to note that steel as a building material is already seen as sustainable due to its recyclability. While recycling steel does promote sustainable practices, after the steel has been recycled it must be remanufactured before it can be reintroduced into the market. Remanufacturing steel includes crushing / shredding, sorting, melting, and fabrication of the steel members. This process is energy intensive and increases the emission of carbon into the atmosphere. In 2021 alone, around 87 million tons of steel was produced in the United States.[5] Our study aims to show that while recycling steel is important in a global context, the United States should also focus on implementing circular economic principles such as steel reuse to reduce the energy and carbon stress that steel manufacturing causes.

Steel is seen as sustainable due to its recyclability, yet this includes crushing, shredding, sorting, melting, and fabrication of new steel members. This process is energy intensive and increases the emission of carbon into the atmosphere.



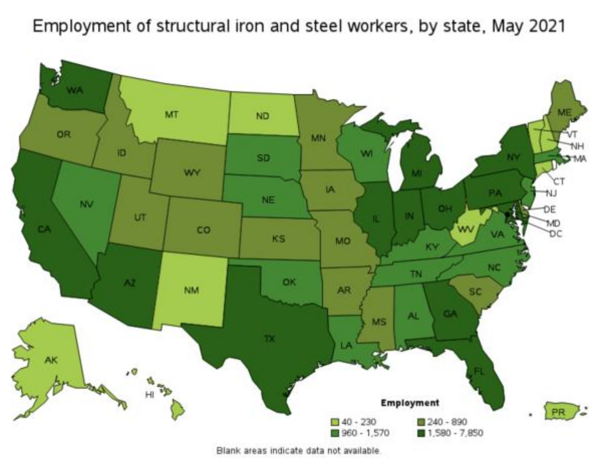


Figure 3.1 (Left) Map of Pittsburgh showing the location of Furnaces, Rolling Mills, & Steel Works[6], Figure 3.2 (Right) Employment of structural iron and steel workers by state in 2021[7]

LITERATURE REVIEW

The literature studied did not outline its relevance within Pittsburgh's context of construction and deconstruction as most studies were based in the UK and Europe. It also

[4] U.S. Bureau of Labor Statistics. "Ironworkers" https://www.bls.gov/ooh/construction-and-extraction/structural-iron-and-steel-workers.htm#tab-1
[5] Statista Research Department. April 28, 2022. "Steel Production Figures U.S. 2006-2021." https://www.statista.com/statistics/209343/steel-production-in-the-us/.
[6] Harvard University, Harvard Map Collection. May 8, 1879. "Map of Pittsburgh showing the location of Furnaces, Rolling Mills, & Steel Works." https://iiif.lib.harvard.edu/manifests/view/ids:11138734$1i.
[7] U.S. Bureau of Labor Statistics. May, 2021. "Occupational Employment and Wage Statistics: Structural Iron and Steel Workers." https://www.bls.gov/oes/current/oes472221.htm#st

lacked information in terms of the effect of steel connection type on the deconstruction method used and corresponding reuse potential in terms of the cost, time and material salvaged. The estimation of steel structures is mostly done for super structures as a whole.

Structural Reuse Potential

Research shows that reuse of steel as a structural element is quite rare, even though there are benefits such as a reduction in CO2 emissions and other sustainable benefits. Due to the repurposed components' uncertain capacities like lack of information regarding a "stress history" of a steel member throughout the lifespan of the steel's serviceable life. In order for a steel member to be reused, strain should be tested on the member to see if the steel is still performing as it should. Regardless, this is a prejudice and the "reuse of structural steel members as new steel members is possible,"[8] based on the tests that were run on a sample set of buildings and the findings from those testings. Studies in the United Kingdom have shown that only situations when reused steel members were less expensive compared to new steel elements is, reusing steel which is located and available from a nearby site and preventing the need to retest the steel elements.[9] Not testing before reusing is a safety hazard and the testing's financial burden and storage support falls upon the steel work contractors and the "stockists" which often discourages them from reusing steel directly. Therefore, studying the economic impact of these tests is an important part of reuse potential study.

The potential need for more extensive deconstruction to separate other components on steel for its reuse is another concern. Certain building characteristics like transparency, regularity, simplicity, and separability simplifies the job of the dismantler and reduces the time and expense of salvaging building materials.[10] Therefore materials that adhere to steel should be avoided as it makes it difficult to separate during deconstruction. However, given that low-rise buildings frequently lack steel fireproofing, which can be challenging to remove, they are particularly appealing for structural steel reuse.[11] Low-rise buildings also make deconstruction operations more effective as well. Lastly, gaps in the supply chain of reused steel and traceability of the required size and shape of the material have been identified as a major barrier for steel reuse potential.[12] Material passports creating a database that house type, size and shape of steel members available shared with suppliers and buyers could help solve this barrier. Digital tracking

[8] Keller, Philipp. *Construction Monitoring, Laboratory Testing, and Finite Element Analysis to Evaluate Reuse Potential of Structural Steel*, University of Delaware, Ann Arbor, 2019. *ProQuest*, https://www.proquest.com/dissertations-theses/construction-monitoring-laboratory-testing-finite/docview/2288856057/se-2.

[9] Dunant, C. F., Drewniok, M. P., Sansom, M., Corbey, S., Cullen, J. M., & Allwood, J. M. (2018). Options to make steel reuse profitable: An analysis of cost and risk distribution across the UK construction value chain. *Journal of Cleaner Production*, *183*, 102-111.

[10] Webster, M. D., & Costello, D. T. (2005, November). Designing structural systems for deconstruction: how to extend a new building's useful life and prevent it from going to waste when the end finally comes. In Greenbuild Conference, Atlanta, GA (p. 14).

[11] Yeung, J. (2016). Development of analysis tools for the facilitation of increased structural steel reuse.

[12] Dunant, C. F., Drewniok, M. P., Sansom, M., Corbey, S., Allwood, J. M., & Cullen, J. M. (2017). Real and perceived barriers to steel reuse across the UK construction value chain. *Resources, Conservation and Recycling*, *126*, 118-131.

of these members at city level storages can also help locate them.[13] Pittsburgh has a high potential for urban steel mining due to its large inventory of steel structures which can be used for optimal reuse of steel.

Connection types

The potential need for more extensive deconstruction strategies to separate the steel components for their reuse is another concern. Certain building characteristics like transparency, regularity, simplicity, and separability simplifies the job of the dismantler and reduces the time and expense of salvaging these building materials.[14] Therefore materials that "permanently" adhere to steel should be avoided as it makes separation during deconstruction difficult. However, given that low-rise buildings frequently lack steel fireproofing, which can be challenging to remove, they are particularly appealing for structural steel reuse.[15] Low-rise buildings also make deconstruction operations more effective as well.

Estimation of steel structures

Our literature review highlighted two steel construction estimates that we were able to use as examples when framing our initial estimate templates. Where our estimates and the literature we studied differ is the introduction of steel connection types which outlines a difference in cost, time, and reuse potential. The first steel structure estimate[16] did introduce the idea of different connection types, but the literature only focuses on the plates that were used to connect the steel members and not the type of connection nor does the literature compare the different connection types in terms of cost or time. The second estimate we studied focused on the basics of cost estimation of a steel superstructure[17], this example helped us determine the initial structure but again the idea of differing connection types was not utilized.

Therefore, our research work focuses on steel buildings in Pittsburgh and identifies their reuse potential based on their connection type, barriers for deconstruction and reuse; while outlining recommendations which can help promote the circularity of steel in Pittsburgh.

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[13] Tingley, D. D., Cooper, S., & Cullen, J. (2017). Understanding and overcoming the barriers to structural steel reuse, a UK perspective. *Journal of Cleaner Production*, *148*, 642-652.

[14] Webster, M. D., & Costello, D. T. (2005, November). Designing structural systems for deconstruction: how to extend a new building's useful life and prevent it from going to waste when the end finally comes. In Greenbuild Conference, Atlanta, GA (p. 14).

[15] Yeung, J. (2016). Development of analysis tools for the facilitation of increased structural steel reuse.

[16] CPE Candidate No. 0115808. July 7, 2015. "How to estimate the cost of different structural beam and column connections."
https://cdn.ymaws.com/www.aspenational.org/resource/resmgr/Techical_Papers/2015_November_Tp.pdf

[17] CPE Candidate No. 0113008. June 2013. "How to estimate the cost of a steel superstructure for a multi-story medical office building at design development."
https://cdn.ymaws.com/www.aspenational.org/resource/resmgr/Techical_Papers/2013_October_TP.pdf

PROBLEM STATEMENT & RESEARCH QUESTIONS

Achieving circularity in the use of steel as a material is a challenge which can be solved by maximizing its reuse and recycling potential. In the current scenario, steel recycling is being implemented within the United States at a very good rate and is benefiting the industry by reducing the energy consumption and carbon for production by 50%. However, reuse of steel is something that is still way behind in its achievable potential. There are multiple factors like cost and time, historic significance, stakeholders vision, space efficiency, age of the building and components, reuse/recycling technology availability, storage/handling spaces, construction techniques used etc. which affect the reuse potential for steel. Our study, however, is only intended to study the implications of steel connection techniques on its reuse potential. Reusing steel is significantly more beneficial than recycling it, as recycling steel is very energy exhausting. In this paper we are trying to understand the benefits and limitations associated with different steel connection techniques available within the construction industry in the US. Understanding this would help understand and improve the potential of steel reuse in the construction industry.

Research Question

How do steel connection types compare in terms of construction and deconstruction in the context of cost, time, and material salvageability for Pittsburgh?

METHODOLOGY

The research is conducted in three phases. Phase 1 is a case study. Phase 2 is estimation of construction and deconstruction cost and scheduling for the three steel connection types and Phase 3 is visual simulation study.

Phase 1- Case Study

We studied the adaptive reuse of Mill-19, a former factory building that has been transformed into an office space to understand the reuse potential of its steel based on the age of the building, age of the components, and its dependence on the type of steel connection techniques used. We documented the steel connections, retrofit and reuse strategies used in the building, and their corresponding time and cost impact on the project. Finally, the estimated lifespan of the new office structure helped us understand the durability of reuse steel. The case study also helped us understand other factors which affect steel reuse decision making in the market like stakeholders, and historic significance.

Phase 2- Estimation

We used a simple steel structure to compare three commonly used steel connection techniques in the market to show how a similar structure if constructed and deconstructed using these techniques can have an impact on the cost (construction and deconstruction), time (time taken to construct and deconstruct), and reuse potential (quantity of steel that is deemed as construction waste and is then taken to be recycled while constructing and deconstructing the building). Our Mill 19 case study along with other available resources like RS Means data were used to calculate the cost and time as a result of labor, material and equipment in Pittsburgh.

The process of this study was as follows:

- Understand the process, cost, equipment, labor and time taken for each step of the construction technique.
- Create schedules and cost sheets for the different iterations.
- Provide comparative analysis in discussions.

Phase 3- Simulation Study

Based on the time labor rates given in RSMeans, we were able to create a simulation study comparing the time it would take to construct or deconstruct the three different connection types.

The process of this study was as follows:

- Understand the process and time taken for each step of the process.
- Develop 3D models in Revit.
- Generate simulations on Navisworks.
- Provide comparative analysis in discussions.

FINDINGS

Phase 1- Case Study - Mill 19, Hazelwood Greens, Pittsburgh

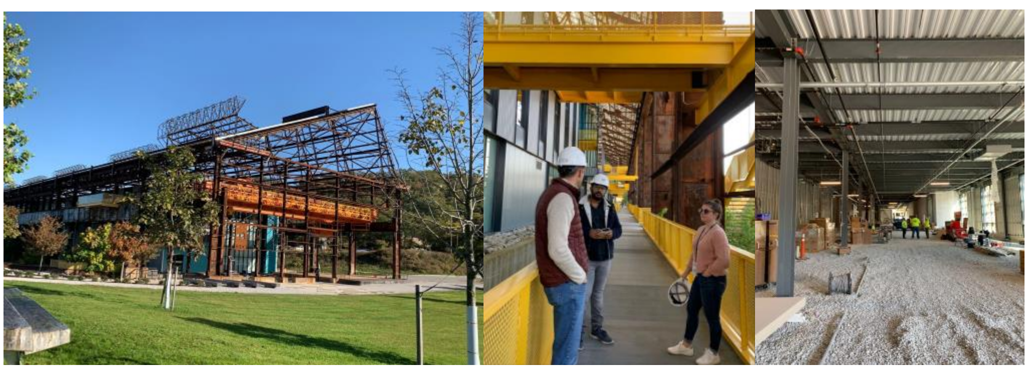

Fig 3.3 Image shows the existing steel mill of Hazelwood reused into commercial office building (Image Source: Shah, 2022)

Vision Statement*:** Historically preserved landmark building built using sustainability principles to/ inspire the development of the neighboring Hazelwood Greens barren land parcels. ***Use: Reuse of Steel Mill to house three Class A Office/Flex space Buildings ***Building Age*:** Originally built in 1943 intended to use for the 60-70 more years	***Building footprint*:** 120,000 sq ft (100 ft x 1200 ft) ***Built up*:** 255,000 usable area (divided in 3 stories) ***Developer*:** RIDC ***AE Team*:** MSR Architects and Consultants

Initial Reuse Intention, Barriers and Outcomes

The initial reports[18] conducted by CEC Company studied the structural strength, weldability, and durability of the old steel building for preliminary design considerations. Tests on the original steel mill showed reuse lifespan as a new building to be 60-70 years. Therefore, the new building was initially designed to use the old building's structural members. However, during the design development phase it was realized that the program requirement for new offices was much less than the mill's size. This would result in unnecessary heating and cooling of spaces which would be problematic for LEED certification and envelope commissioning. There could be problems working very close to the original foundations of the mill columns, and treating the mill envelope for the new building for waterproofing, the rust prevention paint could cost around 15 million USD every four to five years to maintain the building. Around 300 beams of the same size required for the project were not available from the old structure. Thus, from economic, technical and maintenance standpoint the reuse of the original members as a part of the new building was dropped and the new building was constructed within the old structure.

From an economic, technical, and maintenance standpoint the reuse of the original members as a part of the new building was dropped and the new building was constructed within the old structure.

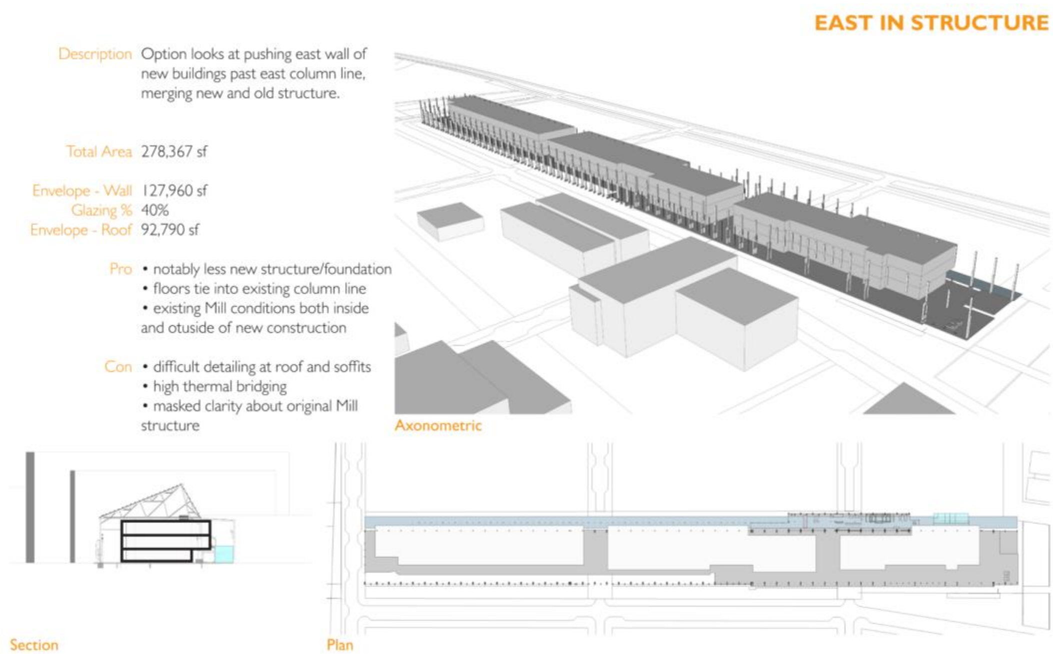

Fig 3.4 Image showing initial building design intent to integrate the old and new buildings. (Image Source: MSR Design)

Instead, the team focused on careful deconstruction of the excess steel from the structure for natural light, reducing deadweight on structure, replacing rusted connections, moving equipment and building materials on site for construction of new buildings. These salvaged steel components were used for landscape elements like

[18] MSR Design (2015) RIDC Mill 19 Steel Analysis Report

railings, ramps, benches, and swings on site. The design for landscape was thus customized based on the salvaged steel available. Since the old building is still encasing the new structure, supporting fire staircases and the solar roof panels there is a structural inspection run every year to check if any members need replacement.

"Hence due to technical and economic barriers, selective demolition of the structure was carried out instead, both structures were independently designed and deconstructed steel is used on site for various other non-structural purposes." Jeryl Aman, Architect, MSR Design

Reuse of the Steel Building and Components

Existing Roof support and slope used for solar panel installation. Helped with sustainability criteria, production of renewable energy, energy savings. Further they were used to support the open cantilevered fire egress staircases and balconies which saved the cost of fireproofing and additional support. The obtained steel was also used in non designed structures on site like parking sheds and to support entrance ramps, make railings, steel furniture (benches, double height swings), etc. in common spaces, where the size of the steel available did not matter much.

Fig 3.5 Steel Reused on Site (Image Source: Shah, 2022)

Existing Steel Connections Observed in the Building

a) Riveted connection	b) Welded Connection	c) Bolted connection
		
Used everywhere in the old steel mill structure only	Used mainly in cantilevered new spaces of the new building.	Used in the new office spaces core and shell structure
Highest cost and time intensive to construct because steel is both welded and bolted so not commonly used in new constructed steel buildings	Costlier and time intensive than bolted connection as requires skilled welders, third party inspectors and more safety measures on site so used only when structurally necessary in project.	Lowest labor and equipment intensive technique, faster in connecting components and inspection time taken, safer for workers to use so commonly used in new constructed buildings

Fig 3.6 Existing Steel Connections observed in the building site (Image Source: Shah, 2022)

Phase 2- Reuse Potential based on Connection Type

The findings show that the construction and deconstruction cost, time taken, and material salvaged are different depending on connection type, therefore affecting the reuse potential of steel. To study these differences, we created a steel prototype structure and estimated these values under three different connection type scenarios: bolted, welded, and riveted.

The prototype structure was a three-story building, made up of 24 W12x87 steel columns (8 columns per floor), 18 W8x48 steel beams (6 per floor), and 66 W6x20 steel rafters (22 on each floor). The gross square footage of the building is 10,538.85 sq ft or 3,512.95 sq ft per floor. These values played an integral role in the calculations and the estimates of the different types of connections.

Gross Building Area	SQFT
1st Floor	3,512.95
2nd Floor	3,512.95
3nd Floor	3,512.95
Gross Square Footage	10,538.85

Floor Structure Takeoff	Quantity	Tons
Steel Columns		
W12x87 - ~3m high - (8 columns per floor)	24	7.64
Steel Beams		
W8x48 - floor 1	6	3.12
W6x20 - floor 1	22	5.48
W8x48 - floor 2	6	3.12
W6x20 - floor 2	22	5.48
W8x48 - floor 3	6	3.12
W6x20 - floor 3	22	5.48
Total	108	33.4

Figure 3.7: Steel Structure Breakdown

Figure 3.8: Steel Structure in Revit

Bolted Connections

Bolted joints are recommended when a project would like to save a considerable amount in regard to cost and time. Bolted connections can prove to be more difficult to engineer because failure of a single connection point can cause failure to the entire structure. Due to the impermanence of the connection point as bolted connections can be removed, the structure can then be designed for deconstruction. It is important to note that distortions can occur over time as the structure ages which can make deconstruction more difficult to complete. Bolted connections have a greater possibility of the structure being deconstructed in the future, with the ability to maximize the amount of material that is reused.

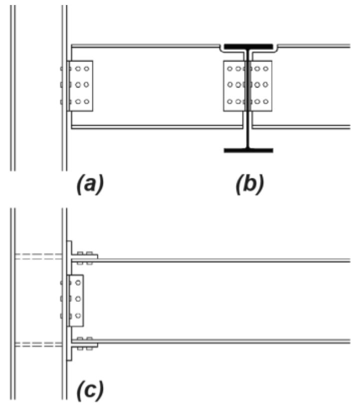

Figure 3.9: Typical bolted Connections for steel members[19]

In the case of our structure, the building's columns were supported by anchor bolts and the beams and rafters supply the use of high strength A490 bolts, nuts, and washers. The bolt hole calculations for this project were completed using the AISC *Steel Construction Manual*[20] and Chapter 4 - Steel: Connections in Jonathan Ochshorn's *Structural Elements for Architects and Builders*[21] as well as values given directly from the Revit model. For the three-story structure, the use of 1 ¼" high strength A490 bolts was determined. The columns have a total of 16 bolts, 8 on each side of the column for a total of 32 bolts per column. The beams have a total of 8 bolts, 4 on each side of the beam which are attached to the columns using steel L-shaped angle plates for a total of 16 bolts per beam. The rafters are attached to the beams with 4 bolts, 2 on each side of the rafter using L-shaped angle plates for a total of 8 bolts per rafter. In total it was estimated that the entire structure will use around 1,584 bolts during its construction. Noting Figure 3.9, connection (a) highlights how the beams and columns will be connected using plates and connection (b) is a visual representation of the beam to rafter connection using plates again.

Construction

During the process of construction, bolted connections rely on hoisting and setting the steel members; bolts are then added (a minimum of two) and fastened using an impact wrench. Bolting is preferred over other types of connections due to the equipment required, experience of the workers, and the installation times.[22] The steps of erecting a bolted steel structure is shown below. Bolted connections also needed to pass inspection, which includes bolt stick-out. This inspection reviews the amount of the bolt that extends past the outside surface of the nut. Bolts fail inspection if there is a negative stick-out or the end of the bolt falls inside of the nut.

[19] Ochshorn, Jonathan. "Chapter 4 - Steel: Connections." Essay. In *Structural Elements for Architects and Builders*, 3rd ed. Ithaca, NY: Jonathan Ochshorn, 2020.
[20] AISC. 2005. "Steel Construction Manual," 13th Edition, American Institute of Steel Construction.
[21] Ochshorn, Jonathan. "Chapter 4 - Steel: Connections." Essay. In *Structural Elements for Architects and Builders*, 3rd ed. Ithaca, NY: Jonathan Ochshorn, 2020.
[22] The Constructor. June 4, 2020. "How to Perform Electric Arc Welding in Steel Structures?" https://theconstructor.org/practical-guide/electric-arc-welding-steel-structure/43176/.

Process and Cost Centers

Figure 3.10 shows the process involved for constructing a bolted structure. Each step represents a cost center with its respective cost estimate and attached schedule. The total duration for construction using bolting was found to be 90 days.

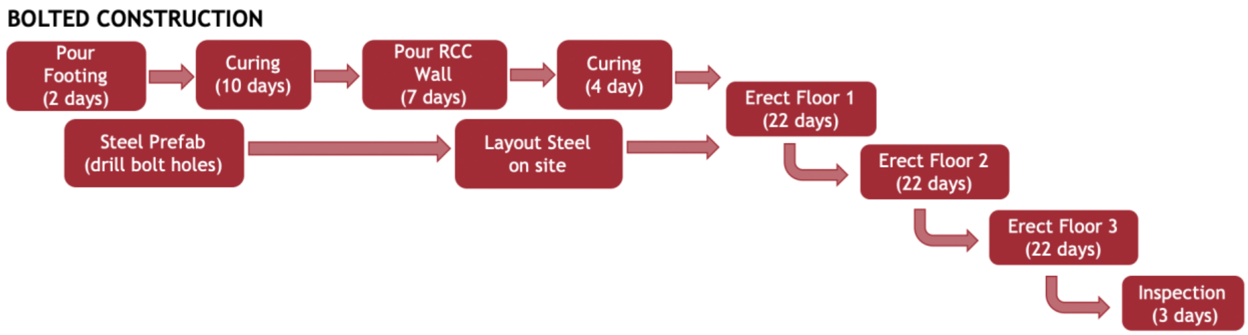

Figure 3.10: Bolted Construction Timeline

RSMeans Database was used to calculate the cost estimate. For the construction of bolted connections the extended overhead and profit total was found to be $236,053.33.

RSMeans data from GORDIAN

COST ESTIMATE REPORT
DATE: 12/14/2022

Estimate Name: Steel Structure - Bolted Connection

ESTIMATE INFORMATION

Client Name:
Estimate Address: Pittsburgh, Pennsylvania
Type: Unit
Measurement System: US Standard
Notes:

COST DATA

Estimate Summary:

	Material	Labor	Equipment	Total*
Base Total	$ 167,422.66	$25,665.88	$11,012.76	$204,101.30
Total O&P	$ 184,629.20	$39,302.73	$12,121.40	$236,053.33

"Total" column values include the cost of Exception lines that may not be included in the Material, Labor and Equipment totals.

Catalog: Commercial New Construction
Format: MasterFormat 2018
Release: Year 2023
Labor Type: Standard Union
City Cost Index: PENNSYLVANIA / PITTSBURGH (150-152)

LEGEND

Line Source: U - User defined line item
A - Adjustment/Modifier
E - Exception lines

ESTIMATE

Quantity	LineNumber	Description	Crew	Daily Output	Labor Hours	Unit	Ext. Mat.	Ext. Labor	Ext. Equip.	Ext. Total	Ext. Mat. O&P	Ext. Labor O&P	Ext. Equip. O&P	Ext. Total O&P
1731	051223750140	Structural steel beam or girder, 100-ton project, 1 to 2 story building, W6x20, A992 steel, shop fabricated, incl shop primer, bolted connections	E2	600	0.093	L.F.	$ 63,250.74	$11,078.40	$ 7,633.71	$ 81,962.85	$ 70,278.60	$ 16,946.49	$ 8,395.35	$ 95,620.44
468	051223750540	Structural steel beam or girder, 100-ton project, 1 to 2 story building, W8x48, A992 steel, shop fabricated, incl shop primer, bolted connections	E2	550	0.102	L.F.	$ 41,329.08	$ 3,271.32	$ 2,251.08	$ 46,851.48	$ 45,363.24	$ 5,012.28	$ 2,485.08	$ 52,860.60
236	051223177200	Column, structural, 2-tier, W12x87, A992 steel, incl shop primer, splice plates, bolts	E2	984	0.057	L.F.	$ 37,847.32	$ 925.12	$ 634.84	$ 39,407.28	$ 41,441.60	$ 1,408.92	$ 698.56	$ 43,549.08
11	015433401580	Rent air tool, impact wrench up to 3/4" bolt, Incl. Hourly Oper. Cost.		0	0	Day	$ -	$ -	$ 493.13	$ 493.13	$ -	$ -	$ 542.41	$ 542.41
1584	050523251600	High strength bolt, 1-1/4" dia x 3" L, A490, incl washer & nut	1 Sswk	85	0.094	Ea.	$ 24,995.52	$10,391.04	$ -	$ 35,386.56	$ 27,545.76	$ 15,935.04	$ -	$ 43,480.80
Grand Total										***$ 204,101.30***				***$ 236,053.33***

Figure 3.11: RSMeans data for construction of bolted connections

Deconstruction

Bolted structures can be disassembled through the process of unbolting each steel member. It is important to note that if the bolded steel members are exposed throughout its lifetime to the elements rust will begin to form making it difficult to remove the bolt. In this case the bolted section would have to be cut off. In our scenario we assumed the structure would eventually be enclosed therefore the structure would be protected from the elements and the rusting process would be significantly delayed allowing for the structure to be deconstructed. The deconstruction process follows a similar path of the bolted construction process. Bolting is preferred over other types of connections due to the equipment required, experience of the workers needed to deconstruct.[23] While deconstruction of bolted structures may be more economical, it is important to note that the scheduling found that it would take the longest compared to the other connection types.

Process and Cost Centers

Figure 3.12 shows the process involved for deconstructing a bolted structure. Each step represents a cost center with its respective cost estimate and attached schedule. The total duration for construction using bolting was found to be 40 days.

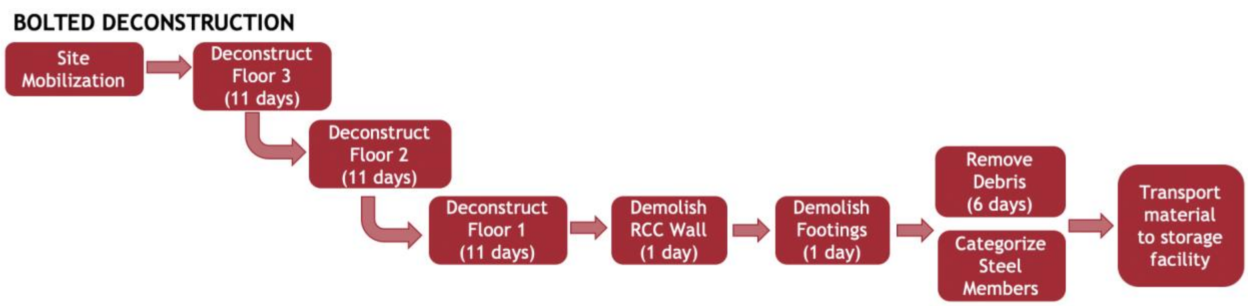

Figure 3.12 Bolted deconstruction timeline

RSMeans Database was used to calculate the cost estimate. For the deconstruction of bolted connections the extended overhead and profit total was found to be $20,683.22.

[23] "How to Perform Electric Arc Welding in Steel Structures? [PDF]." The Constructor, June 4, 2020. https://theconstructor.org/practical-guide/electric-arc-welding-steel-structure/43176/.https://theconstructor.org/practical-guide/electric-arc-welding-steel-structure/43176/

RSMeans data from GORDIAN

COST ESTIMATE REPORT
DATE: 12/14/2022

Estimate Name: Steel Structure - Bolted Connection Deconstruction

ESTIMATE INFORMATION

Client Name:
Estimate Address: Pittsburgh, Pennsylvania
Type: Unit
Measurement System: US Standard
Notes:

COST DATA

Estimate Summary:

	Material	Labor	Equipment	Total*
Base Total	$ -	$ 10,289.28	$ 3,129.60	$ 13,418.88
Total O&P	$ -	$ 17,229.42	$ 3,453.80	$ 20,683.22

"Total" column values include the cost of Exception lines that may not be included in the Material, Labor and Equipment totals.

Catalog: Commercial New Construction
Format: MasterFormat 2018
Release: Year 2023
Labor Type: Standard Union
City Cost Ind PENNSYLVANIA / PITTSBURGH (150-

LEGEND

Line Source: U - User defined line item
A - Adjustment/Modifier
E - Exception lines

ESTIMATE

Quantity	LineNumber	Description	Crew	Daily Output	Labor Hours	Unit	Ext. Mat.	Ext. Labor	Ext. Equip.	Ext. Total	Ext. Mat. O&P	Ext. Labor O&P	Ext. Equip. O&P	Ext. Total O&P
5	015433401590	Rent air tool, impact wrench up to 1-1/4" bolt, Incl. Hourly Oper. Cost.		0	0	Day	$ -	$ -	$ 415.10	$ 415.10	$ -	$ -	$ 456.60	$ 456.60
1584	050505100070	Selective metals demolition, structural bolts/nuts, 7/8" to 2" diameter, unbolt & remove, excl shoring, bracing, cutting, loading, hauling, dumping	E18	0	0	Ea.	$ -	$ 3,849.12	$ -	$ 3,849.12	$ -	$ 6,478.56	$ -	$ 6,478.56
2	024119180200	Selective demolition, disposal only, urban buildings with salvage value allowed, steel frame, includes loading and 5 mile haul to dump	E18	0	0	C.Y.	$ -	$ 7.96	$ 12.98	$ 20.94	$ -	$ 13.02	$ 14.26	$ 27.28
108	050505100240	framing members, 1/4-2 tons, remove whole or cut up into smaller pieces, incl loading, excl shoring, bracing, cutting, hauling, dumping	E18	0	0	Ea.	$ -	$ 5,868.72	$ 2,550.96	$ 8,419.68	$ -	$ 9,819.36	$ 2,816.64	$ 12,636.00
2	015436501800	Mobilization or demobilization, crane, truck-mounted, over 75 ton, (with chase vehicle)	A3E	2.5	6.4	Ea.	$ -	$ 563.48	$ 150.56	$ 714.04	$ -	$ 918.48	$ 166.30	$ 1,084.78
Grand Total										***$ 13,418.88***				***$ 20,683.22***

Figure 3.13: RSMeans data for deconstruction of bolted connections

Welded Connections

Welded joints are recommended when the structural performance of a project takes higher priority than cost. Welded joints are more rigid and provide higher strength. However, internal and external distortions can happen while the areas of connection are exposed to uneven heating during the process of welding. There are five types: butt, corner, edge, lap and tee welding. These types of joints are determined by the position of welded elements relative to one another.[24]

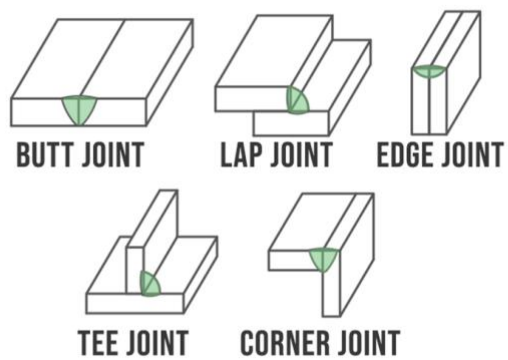

Figure 3.14: Types of welded connections[25]

In our welded steel connection structure, the beam and rafters are connected by Butt and Tee/ Fillet joints. It is common practice within construction to attach the columns to the slab with the use of anchor bolts, so in the case of the steel structure the columns will be attached with bolts. When the surfaces to be joined are on the same plane, then it is a butt weld. If the surfaces are perpendicular (with an angle of 90°), then they are usually joined with a filet weld. Such connections are an efficient and direct means of transferring forces from one member to the adjacent member in the structure. Welded connections are usually constructed by melting the base metal from the parts to join the weld metal, which forms the connection after cooling.[26]

[24] Admin. “Types of Welding Joints and Welding Styles for Preparing Weld Joints.” WeldingInfo, January 18, 2022. https://www.weldinginfo.org/welding-technology/different-types-of-welding-joints/.

[25] Derek Mason. November 10, 2021. “Types of welding joints explained - different welds and styles.” WeldingPros. https://weldingpros.net/types-of-welding-joints/.

[26] “All House Related Solutions,” GharPedia, accessed November 28, 2022, https://gharpedia.netlify.app/blog/beam-to-column-connections/.

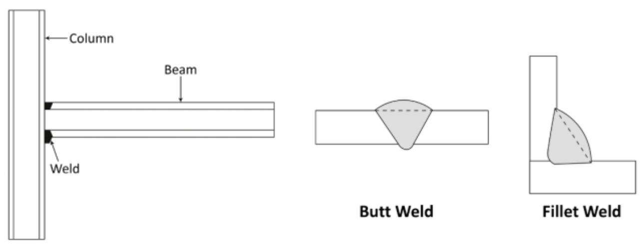

Figure 3.15: Welded connections used in our steel structure[27]

Construction

During the process of construction, welding relies on melting workpieces of Steel to fuse it together. The electric arc welding method is preferred over other methods due to its affordability. Electric arc welding process uses an electric arc to generate heat to melt the parent material and the filler material (electrode) to form a molten weld pool in the joint.[28] The steps of erecting a welded steel structure by electric arc welding method is shown below.

Process and Cost Centers

Figure 3.16 shows the process involved for constructing a welded structure. Each step represents a cost center with its respective cost estimate and attached schedule. The total duration for construction using bolting was found to be 97 days.

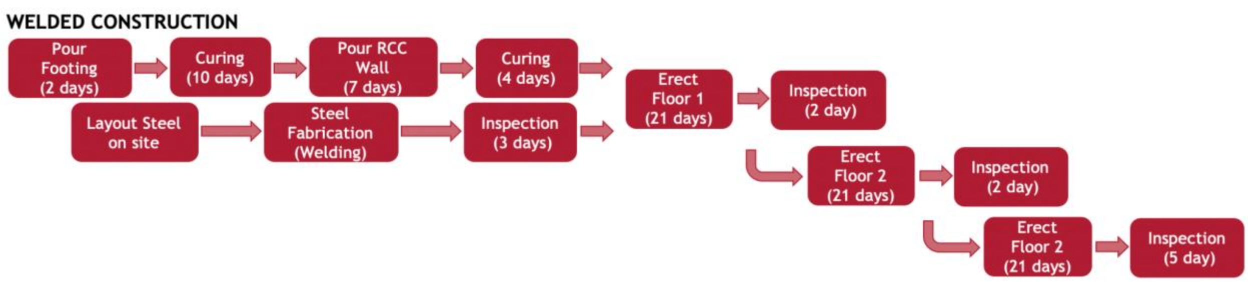

Figure 3.16 Welded construction timeline

RSMeans Database was used to calculate the cost estimate. For the construction of welded connections the extended overhead and profit total was found to be $287,468.54.

[27] Janvi Desai. June 22, 2022. “Beam to column connections in steel structure - types and design procedure.” https://gharpedia.com/blog/beam-to-column-connections/.
[28] The Constructor. June 4, 2020. “How to Perform Electric Arc Welding in Steel Structures?” https://theconstructor.org/practical-guide/electric-arc-welding-steel-structure/43176/.

RSMeans data from GORDIAN

COST ESTIMATE REPORT
DATE: 12/14/2022

Estimate Name: Steel Structure - Welded Connection

ESTIMATE INFORMATION

Client Name:
Estimate Address: Pittsburgh, Pennsylvania
Type: Unit
Measurement System: US Standard
Notes:

COST DATA

Estimate Summary:

	Material	Labor	Equipment	Total*
Base Total	$ 146,242.26	$ 43,105.42	$ 15,276.79	$ 244,447.31
Total O&P	$ 161,284.84	$ 65,646.31	$ 16,775.79	$ 287,468.54

"Total" column values include the cost of Exception lines that may not be included in the Material, Labor and Equipment totals.

Catalog: Commercial New Construction
Format: MasterFormat 2018
Release: Year 2023
Labor Type: Standard Union
City Cost Ind PENNSYLVANIA / PITTSBURGH (150-152)

LEGEND

Line Source:
U - User defined line item
A - Adjustment/Modifier
E - Exception lines

ESTIMATE

Quantity	LineNumber	Description	Crew	Daily Output	Labor Hours	Unit	Ext. Mat.	Ext. Labor	Ext. Equip.	Ext. Total	Ext. Mat. O&P	Ext. Labor O&P	Ext. Equip. O&P	Ext. Total O&P
3	015433401590	Rent air tool, impact wrench up to 1-1/4" bolt, Incl. Hourly Oper. Cost.		0	0	Day	$ -	$ -	$ 249.06	$ 249.06	$ -	$ -	$ 273.96	$ 273.96
128	050523251600	High strength bolt, 1-1/4" dia x 3" L, A490, incl washer & nut	1 Sswk	85	0.094	Ea.	$ 2,019.84	$ 839.68	$ -	$ 2,859.52	$ 2,225.92	$ 1,287.68	$ -	$ 3,513.60
168	050521900300	Welding structural steel in field, cost per welder, 1/8" dia, type 6011, incl 1 operating engineer	E12	8	2	Hr.	$ 1,354.08	$ 22,777.44	$ 3,042.48	$ 27,174.00	$ 1,490.16	$ 34,527.36	$ 3,306.24	$ 39,323.76
108	014523506100	Welding certification, maximum		0	0	Ea.	$ -	$ -	$ -	$ 39,822.84	$ -	$ -	$ -	$ 43,761.60
1103	050521901300	Welding structural steel in field, single pass, 0.1 lb/LF, 1/8" thick, continuous fillet, down welding, type 6011	E12	0	0	L.F.	$ 441.20	$ 4,213.46	$ 1,058.88	$ 5,713.54	$ 485.32	$ 6,463.58	$ 1,169.18	$ 8,118.08
6	015433407700	Rent arc welder electric 200 amp, Incl. Hourly Oper. Cost.		0	0	Day	$ -	$ -	$ 406.74	$ 406.74	$ -	$ -	$ 447.42	$ 447.42
236	051223177200	Column, structural, 2-tier, W12x87, A992 steel, incl shop primer, splice plates, bolts	E2	984	0.057	L.F.	$ 37,847.32	$ 925.12	$ 634.84	$ 39,407.28	$ 41,441.60	$ 1,408.92	$ 698.56	$ 43,549.08
468	051223750540	Structural steel beam or girder, 100-ton project, 1 to 2 story building, W8x48, A992 steel, shop fabricated, incl shop primer, bolted connections	E2	550	0.102	L.F.	$ 41,329.08	$ 3,271.32	$ 2,251.08	$ 46,851.48	$ 45,363.24	$ 5,012.28	$ 2,485.08	$ 52,860.60
1731	051223750140	Structural steel beam or girder, 100-ton project, 1 to 2 story building, W6x20, A992 steel, shop fabricated, incl shop primer, bolted connections	E2	600	0.093	L.F.	$ 63,250.74	$ 11,078.40	$ 7,633.71	$ 81,962.85	$ 70,278.60	$ 16,946.49	$ 8,395.35	$ 95,620.44
Grand Total										***$ 244,447.31***				***$ 287,468.54***

Figure 3.17: RSMeans data for construction of welded connections

Deconstruction

It is very difficult to undo welded joints in a welded steel structure. These joints need to be separated by cutting to be able to reuse the steel member. Deconstruction can be done using mechanical methods like saw cutting or grinding or using thermal methods like plasma cutting or oxyacetylene gas torches.[29] The flame cutting methods are faster and more economical than the mechanical methods and can cut shapes and dimensions of steel which mechanical methods cannot. However, the residue they leave on site can be a safety hazard to the workers and the environment. The fumes need to be controlled properly and the site requires proper ventilation. The equipment requires additional setup like gas tanks or compressors on site and therefore mechanical cutters are commonly used over thermal methods.

Process and Cost Centers

Figure 3.18 shows the process involved for deconstructing a welded structure. Each step represents a cost center with its respective cost estimate and attached schedule. The total duration for construction using bolting was found to be 30 days.

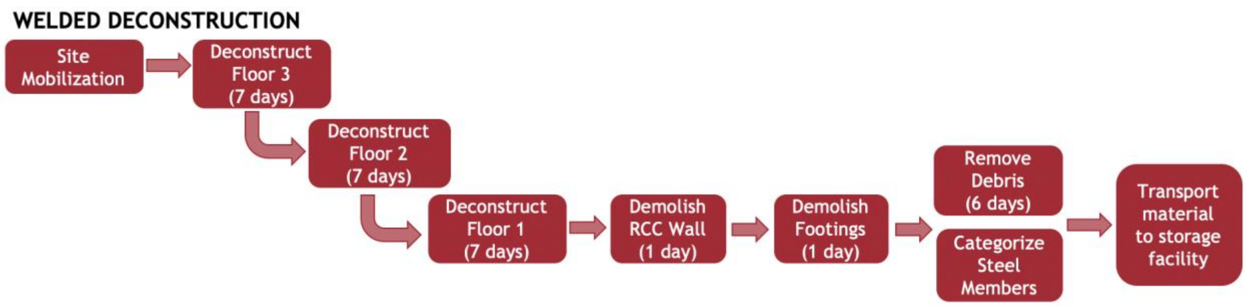

Figure 3.18 Welded deconstruction timeline

RSMeans Database was used to calculate the cost estimate. For the deconstruction of welded connections the extended overhead and profit total was found to be $42,251.04.

[29] Pierre Young, "How to Remove Welding," Welding Headquarters, June 6, 2022, https://weldingheadquarters.com/how-to-remove-welding/.

RSMeans data from GORDIAN

COST ESTIMATE REPORT
DATE: 12/14/2022

Estimate Name: Steel Structure - Welded Connection Deconstruction

ESTIMATE INFORMATION

Client Name:
Estimate Address: Pittsburgh, Pennsylvania
Type: Unit
Measurement System: US Standard
Notes:

COST DATA

Estimate Summary:

	Material	Labor	Equipment	Total*
Base Total	$ 3,603.90	$15,435.62	$13,378.60	$32,418.12
Total O&P	$ 3,972.90	$23,497.54	$14,780.60	$42,251.04

"Total" column values include the cost of Exception lines that may not be included in the Material, Labor and Equipment totals.

Catalog: Commercial New Construction
Format: MasterFormat 2018
Release: Year 2023
Labor Type: Standard Union
City Cost Ind PENNSYLVANIA / PITTSBURGH (150-

LEGEND

Line Source:
U - User defined line item
A - Adjustment/Modifier
E - Exception lines

ESTIMATE

Quantity	LineNumber	Description	Crew	Daily Output	Labor Hours	Unit	Ext. Mat.	Ext. Labor	Ext. Equip.	Ext. Total	Ext. Mat. O&P	Ext. Labor O&P	Ext. Equip. O&P	Ext. Total O&P
2	024119180200	Selective demolition, disposal only, urban buildings with salvage value allowed, steel frame, includes loading and 5 mile haul to dump	B3	430	0.112	C.Y.	$ -	$ 11.30	$ 12.98	$ 24.28	$ -	$ 16.84	$ 14.26	$ 31.10
108	050505100240	framing members, 1/4-2 tons, remove whole or cut up into smaller pieces, incl loading, excl shoring, bracing, cutting, hauling, dumping	E18	36	1.111	Ea.	$ -	$ 8,366.76	$ 2,550.96	$ 10,917.72	$ -	$12,782.88	$ 2,816.64	$ 15,599.52
1230	050521100200	Cutting, steel, to 1" thick, by hand, incl prep, torch cutting & grinding, excl staging	E25	200	0.04	L.F.	$ 3,603.90	$ 3,517.80	$ 86.10	$ 7,207.80	$ 3,972.90	$ 5,424.30	$ 98.40	$ 9,495.60
5	024210209010	equipment, as needed, daily use, 12-ton truck-mounted hydraulic crane, portal to portal, includes operator, includes operator	A3H	1	8	Day	$ -	$ 2,734.80	$10,578.00	$ 13,312.80	$ -	$ 4,076.40	$11,685.00	$ 15,761.40
2	015436501800	Mobilization or demobilization, crane, truck-mounted, over 75 ton, (with chase vehicle)	A3E	2.5	6.4	Ea.	$ -	$ 804.96	$ 150.56	$ 955.52	$ -	$ 1,197.12	$ 166.30	$ 1,363.42
Grand Total										***$ 32,418.12***				***$ 42,251.04***

Figure 3.19: RSMeans data for deconstruction of welded connections

Riveted Connections

By riveting plates or other components resembling angles to both connecting elements, the riveted connection is created. A "shank," a round bar of ductile steel with a head on one end, makes up a rivet. High tensile steel is used to make it. In our structure, following insertion into the required holes, they are punched against plates to round the end. Layers of steel angles and flat plates were used to reinforce riveted connections. At the steel mill, holes are punched for field riveting before the columns and girders are assembled with rivets and sent to the construction site. Cranes are utilized to position the components, and bolts are employed as temporary connectors to maintain the steel pieces level and plumb as well as to bind them together so that riveting can be done. The bolts are removed to be reused and rivets are substituted for them after rivets have been inserted into all of the holes.

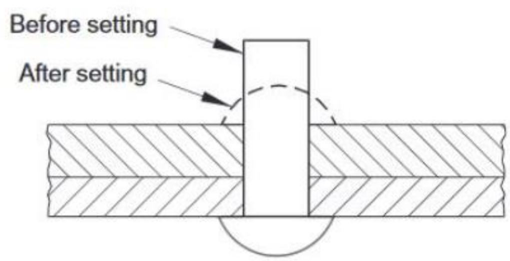

Figure 3.20: Conventional rivet before and after settling[30]

Construction

The riveting construction process begins with the rivets being heated to the appropriate temperature in a furnace resembling a blacksmith's forge, frequently using a mechanical blower or bellows. In order to heat the rivets uniformly and maintain the temperature required for riveting, the tender would maintain a hot fire while turning them with long-handled tongs used along with an accurate pitcher.[31] The structural steel must be riveted rapidly to prevent the rivet from cooling after coming into contact with the air.

Process and Cost Centers

Figure 3.21 shows the process involved for constructing a riveted structure. Each step represents a cost center with its respective cost estimate and attached schedule. The total duration for construction using bolting was found to be 145 days.

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[30] Childs, Peter R.N. 2019. “Riveted Joint.” Essay. *Mechanical Design Engineering Handbook*. Butterworth-Heinemann.

[31] Greg Havel. January 17, 2020. “Construction Concerns: Structural Steel-Riveted Connections,” Fire Engineering: Firefighter Training and Fire Service News, Rescue. https://www.fireengineering.com/fire-prevention-protection/structural-steel-riveted-connections/#gref.

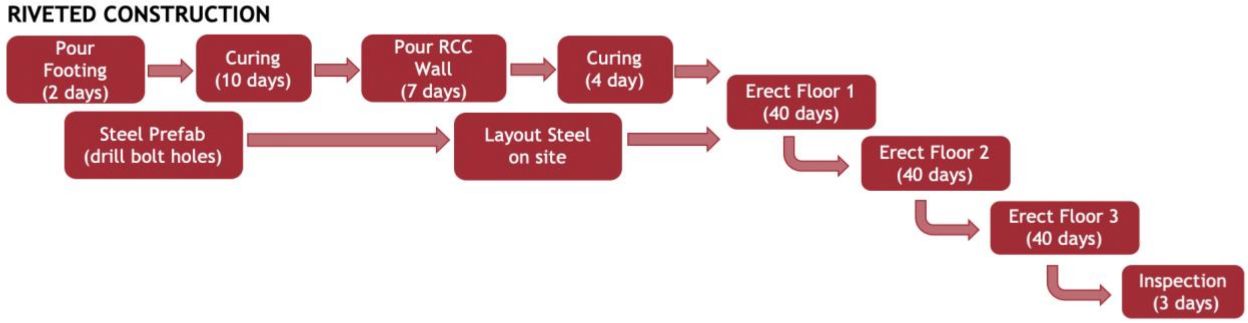


Figure 3.21 Riveted construction timeline

RSMeans Database was used to calculate the cost estimate. For the construction of riveted connections, the extended overhead and profit total was found to be $322,445.88.

RSMeans data from GORDIAN

COST ESTIMATE REPORT
DATE: 12/14/2022

Estimate Name: Steel Structure - Riveted Connection

ESTIMATE INFORMATION

Client Name:
Estimate Address: Pittsburgh, Pennsylvania
Type: Unit
Measurement System: US Standard
Notes:

COST DATA

Estimate Summary:

	Material	Labor	Equipment	Total*
Base Total	$ 148,634.98	$ 98,363.56	$10,519.63	$ 257,518.17
Total O&P	$ 163,931.36	$ 146,935.53	$11,578.99	$ 322,445.88

"Total" column values include the cost of Exception lines that may not be included in the Material, Labor and Equipment totals.

Catalog: Commercial New Construction
Format: MasterFormat 2018
Release: Year 2023
Labor Type: Standard Union
City Cost Ind PENNSYLVANIA / PITTSBURGH (150-

LEGEND

Line Source:
U - User defined line item
A - Adjustment/Modifier
E - Exception lines

ESTIMATE

Quantity	LineNumber	Description	Crew	Daily Output	Labor Hours	Unit	Ext. Mat.	Ext. Labor	Ext. Equip.	Ext. Total	Ext. Mat. O&P	Ext. Labor O&P	Ext. Equip. O&P	Ext. Total O&P
792	050523551200	Rivet, steel rivet and mandrel, 1/2" grip length x 1/8" dia	1 Carp	4.8	1.667	C	$ 4,348.08	$83,088.72	$ -	$ 87,436.80	$ 4,791.60	$123,567.84	$ -	$ 128,359.44
1731	051223750140	Structural steel beam or girder, 100-ton project, 1 to 2 story building, W6x20, A992 steel, shop fabricated, incl shop primer, bolted connections	E2	600	0.093	L.F.	$63,250.74	$11,078.40	$ 7,633.71	$ 81,962.85	$70,278.60	$ 16,946.49	$ 8,395.35	$ 95,620.44
468	051223750540	Structural steel beam or girder, 100-ton project, 1 to 2 story building, W8x48, A992 steel, shop fabricated, incl shop primer, bolted connections	E2	550	0.102	L.F.	$41,329.08	$ 3,271.32	$ 2,251.08	$ 46,851.48	$45,363.24	$ 5,012.28	$ 2,485.08	$ 52,860.60
236	051223177200	Column, structural, 2-tier, W12x87, A992 steel, incl shop primer, splice plates, bolts	E2	984	0.057	L.F.	$37,847.32	$ 925.12	$ 634.84	$ 39,407.28	$41,441.60	$ 1,408.92	$ 698.56	$ 43,549.08
3	050523551600	Power riveting tool, standard		0	0	Ea.	$ 1,859.76	$ -	$ -	$ 1,859.76	$ 2,056.32	$ -	$ -	$ 2,056.32
Grand Total										***$ 257,518.17***				***$ 322,445.88***

Figure 3.22: RSMeans data for construction of riveted Connections

Deconstruction

Since riveted structures cannot be unbolted, they must be cut from the connection point like welded structures. Since the cutting process and length of the cut is similar to welded structures the cost estimate for deconstruction is the exact same value as that for welded structures. However, when the riveting is done at a certain distance from the connection point on the plate the torch cut cannot be made as close to the connection as in case of the welded structures and hence the material salvaged is different. Deconstruction can be done using mechanical methods like saw cutting or grinding or using thermal methods like plasma cutting or oxyacetylene gas torches.[32] The flame cutting methods are faster and more economical than the mechanical methods and can cut shapes and dimensions of steel which mechanical methods cannot. However, the residue they leave on site can be a safety hazard to the workers and the environment. The fumes need to be controlled properly and the site requires proper ventilation. The equipment requires additional setup like gas tanks or compressors on site and therefore mechanical cutters are commonly used over thermal methods.

Process and Cost Centers

Figure 3.23 shows the process involved for deconstructing a riveted structure. Each step represents a cost center with its respective cost estimate and attached schedule. The total duration for construction using bolting was found to be 30 days.

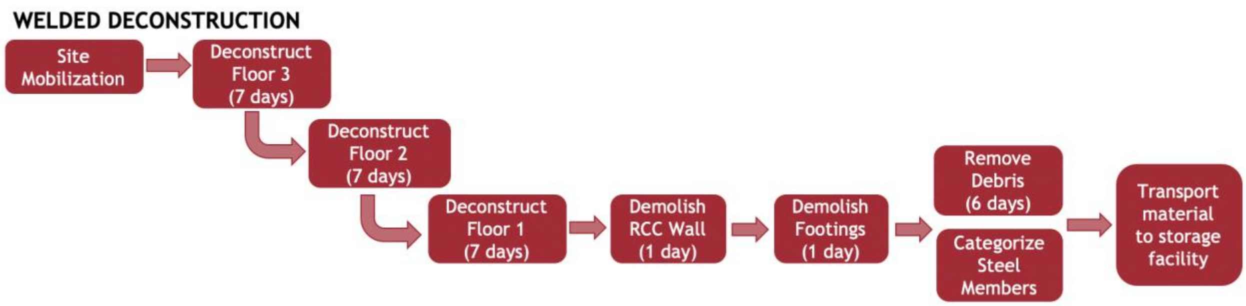


Figure 3.23 Riveted deconstruction timeline

RSMeans Database was used to calculate the cost estimate. For the deconstruction of riveted connections the extended overhead and profit total was found to be $42,251.04.

[32] Pierre Young, "How to Remove Welding," Welding Headquarters, June 6, 2022, https://weldingheadquarters.com/how-to-remove-welding/.

RSMeans data
from GORDIAN®

COST ESTIMATE REPORT
DATE: 12/14/2022

Estimate Name: Steel Structure - Riveted Connection Deconstruction

ESTIMATE INFORMATION

Client Name:
Estimate Address: Pittsburgh, Pennsylvania

Type: Unit
Measurement System: US Standard

Notes:

COST DATA

Estimate Summary:

	Material	Labor	Equipment	Total*
Base Total	$ 3,603.90	$15,435.62	$13,378.60	$32,418.12
Total O&P	$ 3,972.90	$23,497.54	$14,780.60	$42,251.04

"Total" column values include the cost of Exception lines that may not be included in the Material, Labor and Equipment totals.

Catalog: Commercial New Construction
Format: MasterFormat 2018
Release: Year 2023
Labor Type: Standard Union
City Cost Ind PENNSYLVANIA / PITTSBURGH (150-

LEGEND

Line Source:
U - User defined line item
A - Adjustment/Modifier
E - Exception lines

ESTIMATE

Quantity	LineNumber	Description	Crew	Daily Output	Labor Hours	Unit	Ext. Mat.	Ext. Labor	Ext. Equip.	Ext. Total	Ext. Mat. O&P	Ext. Labor O&P	Ext. Equip. O&P	Ext. Total O&P
2	015436501800	Mobilization or demobilization, crane, truck-mounted, over 75 ton, (with chase vehicle)	A3E	2.5	6.4	Ea.	$ -	$ 804.96	$ 150.56	$ 955.52	$ -	$ 1,197.12	$ 166.30	$ 1,363.42
2	024119180200	Selective demolition, disposal only, urban buildings with salvage value allowed, steel frame, includes loading and 5 mile haul to dump	B3	430	0.112	C.Y.	$ -	$ 11.30	$ 12.98	$ 24.28	$ -	$ 16.84	$ 14.26	$ 31.10
5	024210209010	equipment, as needed, daily use, 12-ton truck-mounted hydraulic crane, portal to portal, includes operator, includes operator	A3H	1	8	Day	$ -	$ 2,734.80	$10,578.00	$ 13,312.80	$ -	$ 4,076.40	$11,685.00	$ 15,761.40
108	050505100240	framing members, 1/4-2 tons, remove whole or cut up into smaller pieces, incl loading, excl shoring, bracing, cutting, hauling, dumping	E18	36	1.111	Ea.	$ -	$ 8,366.76	$ 2,550.96	$ 10,917.72	$ -	$12,782.88	$ 2,816.64	$ 15,599.52
1230	050521100200	Cutting, steel, to 1" thick, by hand, incl prep, torch cutting & grinding, excl staging	E25	200	0.04	L.F.	$ 3,603.90	$ 3,517.80	$ 86.10	$ 7,207.80	$ 3,972.90	$ 5,424.30	$ 98.40	$ 9,495.60
Grand Total										***$ 32,418.12***				***$ 42,251.04***

Figure 3.24: RSMeans data for deconstruction of riveted connections

Phase 3- Simulation Study

Fig 3.25 and 3.26 visualize the comparative schedule simulations for the 3 connection types and their respective time taken during each phase in construction and deconstruction. While all the 3 connection types have similar timelines for the initial work packages, they start to vary from erection of steel packages on site. This is mainly because bolted structures can be easily erected using bolts and approved by construction inspector in a day using manual tools, while welded connections can take up to 3 weeks time for inspection and result in the delay on site. A possible solution to reduce this delay can be to prefabricate the steel members and weld them for each floor and then bring them on site for faster assembly. However, it is difficult to achieve that considering the size or the components and additional logistics cost.

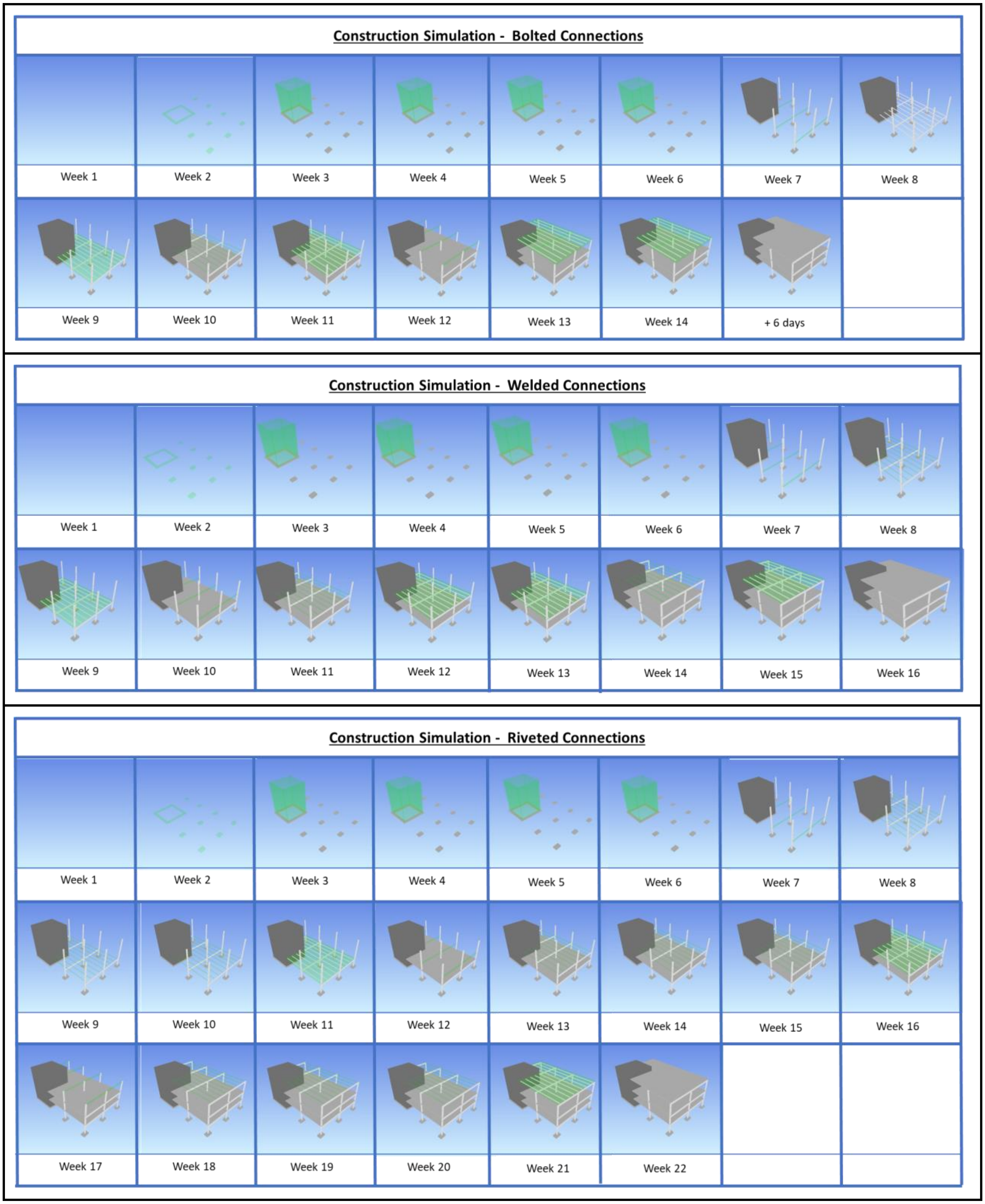


Fig 3.25: Comparative week wise chart for all three connection types for construction based on 4D simulation model study.

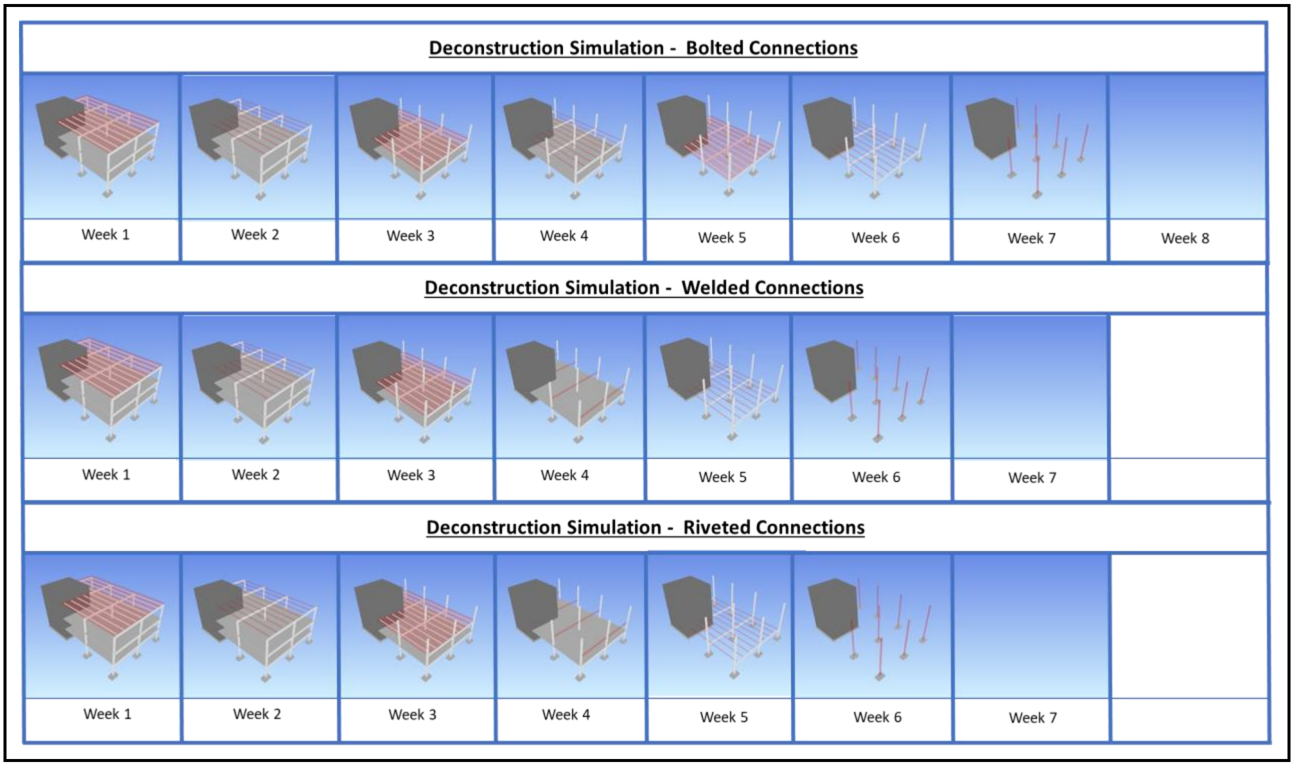


Fig 3.26 Comparative week wise chart for all three connection types for deconstruction based on 4D simulation model study

DISCUSSION

Comparative Analysis

Our comparative analysis section highlights and compares the connection types: bolted, welded and riveted to determine which type is the most beneficial to the construction and deconstruction of steel structures. Welded and riveted structures are 21.78% and 36.59% more expensive to construct than bolted structures and take 8.3% and 62.02% more time respectively. Since, riveted is not used as a connection type for new structures today, it holds significance only for deconstruction study as most old steel buildings built before 1970s in Pittsburgh utilized riveted connections. For deconstruction, while riveted and welded structures are double the cost than bolted structures, they reduce the deconstruction time by around 25%. Hence if time is the priority in terms of deconstruction, welded and riveted connections are the better options. However, it is important to note that the material salvaged for bolted structures post deconstruction is found to be the maximum at 100%, followed by welded structures at 98.24% and riveted structures at 95.6%. Since riveted structures have poor performance for all three criteria, they are not preferable unless structurally required. Bolted and welded structures can be chosen based on the multi criteria decision making by providing weightage to each parameter cost, time and material salvaged for optimal decision making.

Welded and riveted structures are 21.78% and 36.59% more expensive to construct than bolted structures and take 8.3% and 62.02% more time respectively.

Cost

Fig 3.27 compares the cost per sq ft for all the three scenarios for both construction and deconstruction. The results show bolted connections having the best results in terms of lowest cost per sq ft for construction and deconstruction.

Fig 3.27: The cost per sq ft for all three scenarios for construction and deconstruction.

Table 3.1 Construction cost base and total, cost per sq ft for all 3 connection scenarios.

CONSTRUCTION			
Connection	**Base Total**	**Total O&P**	**Cost per SQFT**
Bolted	$ 204,101.30	$ 236,053.33	$ 22.40
Welded	$ 244,447.31	$ 287,468.54	$ 27.28
Riveted	$ 257,518.17	$ 322,445.88	$ 30.60

Table 3.2 Deconstruction cost base and total cost per sq ft for all 3 connection scenarios and general demolition.

DECONSTRUCTION			
Connection	**Base Total**	**Total O&P**	**Cost per SQFT**
Bolted	$ 13,418.88	$ 20,683.22	$ 1.96
Welded	$ 32,418.12	$ 42,251.04	$ 4.01
Riveted	$ 32,418.12	$ 42,251.04	$ 4.01
Demolition	$ 36,991.50	$ 46,476.50	$ 4.41

Time

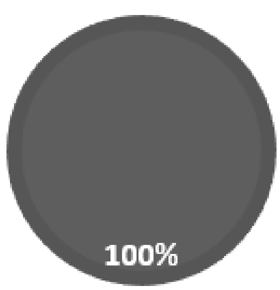
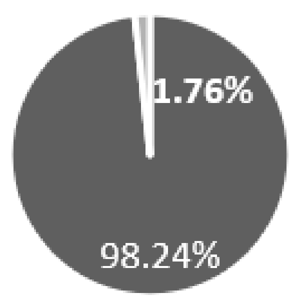
Table 3.3 shows that bolted structures are the fastest to erect however they take more time than welded and riveted structures to deconstruct. This time difference is because unbolting can be difficult in situations where the steel bolts have become rusty. Welding takes more time in construction due to the additional inspections; however, for deconstructing inspection is not required and hence can be done faster.

Table 3.3 Construction and Deconstruction for all 3 scenarios and duration required per sq ft

SCHEDULING	CONSTRUCTION		DECONSTRUCTION	
	Duration (days)	Duration (day/sqft)	Duration (days)	Duration (day/sqft)
Bolted	90 days	0.025 day/sqft	40 days	0.011 day/sqft
Welded	97 days	0.028 day/sqft	30 days	0.008 day/sqft
Riveted	145 days	0.041 day/sqft	30 days	0.008 day/sqft

Material salvaged

Fig 3.28 compares the percentage of material that is salvaged in each case. It can be seen that bolted structures salvage the max. Material for reuse followed by welded and riveted. Since welded and riveted connections require us to cut at the steel member at the joinery section that steel must be sent to recycling. The salvage recycling value of this 2% steel for welded and 4% for riveted connections is given in table 3.4. Table 3.4 also shows the value if the entire building is sent to recycling. It can be seen that almost 33 tons of steel only has a salvage value of $6660 which is on the lower end of the current market value of steel.

Bolted	Welded
	

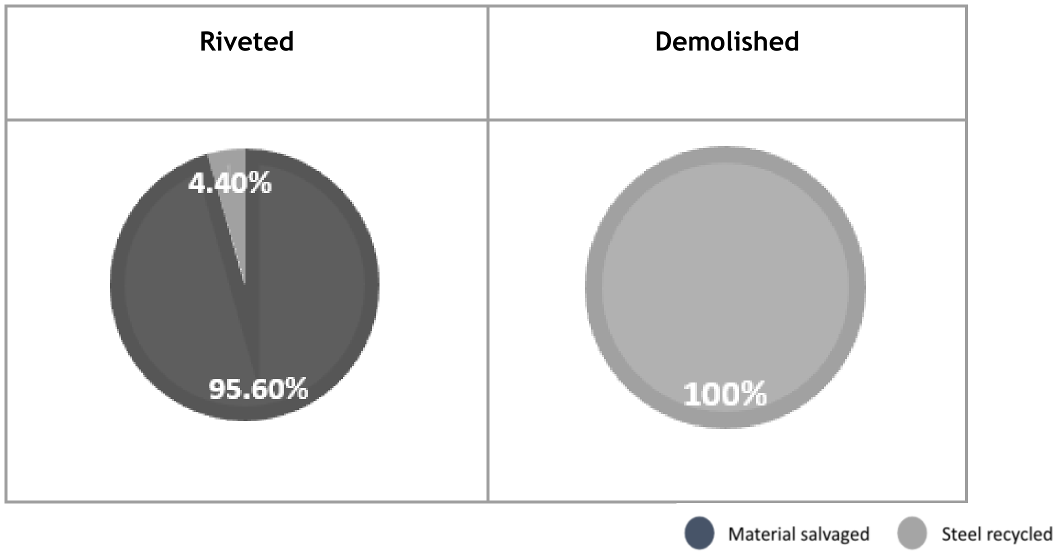


Fig 3.28 The percentage of material that is salvaged for reuse and recycling in each connection type and complete building demolition.

Table 3.4 Salvage value of steel obtained after sending it for recycling and the cost to buy the remanufactured steel.

Material Salvageability				
Connection	lbs of Steel Recycled	Recycled Steel Value Base Total	Recycled Steel Value Total O&P	Remanufactured Steel
Bolted	-	$ -	$ -	$ -
Welded	1,172.83	$ 105.55	$ 117.28	$ 738.26
Riveted	2,931.69	$ 263.85	$ 293.17	$ 1,845.39
Demolished	66,603.32	$ 5,994.27	$ 6,660.30	$ 41,924.41

Recommendations

When it comes to steel, the current practice in the industry is to recycle. While steel is 100% recyclable, we do not recommend that this be the only “sustainable” practice within the steel industry. The high energy consumption used to reprocess and remanufacture the steel, the emissions caused by the production process, and the low salvage value obtained are some of the unintended effects associated with recycling. While we understand recycling might be the easier option, the current industry needs to redirect focus onto reusing steel before it is recycled. At the moment within the United States, steel reuse is not a practice that is currently being utilized, so recycling takes precedence. There are many current unknowns to the practice of steel reuse such as steel recertification, de-constructability of steel structures, and potential cost and time implications surrounding deconstruction, manufacturing, and storage capabilities. Steel reuse could prove to be beneficial to job creation, and industrial revitalization.

The high energy consumption used to reprocess and remanufacture the steel, the emissions caused by the production process, and the low salvage value obtained are some of the unintended effects associated with recycling.

Pittsburgh has a history steeped in steel manufacturing, which makes this city the perfect place to implement these practices. As steel manufacturing and construction continues to play a large role in the future of structures, we think bolted connections could play an important role in de-constructability of structural steel. Bolted steel connections allow for the structure to be taken apart at the building's end-of-life, with only basic equipment and labor force.

Points from designer's and contractor's perspective which could help increase reuse potential of steel are:

- Protecting steel members from weather for increasing reuse lifespan
- Periodic data collection over the service life of the steel for a more well rounded analysis on the reuse capability of the steel.
- Design of steel structures for disassembly and designing based on available salvaged materials.
- Identifying alternatives to cementitious fireproofing.
- Identifying tools for effective and safe deconstruction.
- Finding advanced technology-based solutions for technical barriers faced by contractors for steel reuse.

Limitations

Our study relies on the information that was obtained through the use of RSMeans 2023. This means our study was limited to the line items that were found within the program, we didn't include custom line items because this could affect the outcome of our comparative study. We also followed RSMeans guidelines for time and demolition values, this includes labor values and the salvage value of the demolished steel. Another limitation of our study includes the overall knowledge of the group in regards to the engineering of steel structures. The calculations that were completed to determine the amount of bolts and rivets needed as well as the amount of linear feet of weld was completed using prior knowledge, but might not be an accurate representation of the current practices within the industry.

Future Work

The next steps that need to be taken for this project include a deeper study that needs to be conducted on the steel standardization and recertification process. Research has been completed on this steel recertification process within different countries in Europe, but an in depth study needs to be completed between the certification process in Europe and the proposed process that could be implemented in the United States. The recertification process can include the retesting of the structural steel members to ensure confidence within its new context, data collection, the possibility for re-fabrication, inspection and a full material passport. Testing would include the non-destructive and destructive testing but with the hopes to reuse the structural steel, a destructive test would not be the best option. The recertification process should also include pre-demolition inspection and survey to determine the potential members for reuse. Another step that needs to be taken to move forward with deconstructable steel structures is the

> The next steps that need to be taken are a deeper study focused steel standardization and recertification processes, … policies that incentivize steel reuse, and automated testing technology

storage of the members between deconstruction and refabrication, this would include a full breakdown on cost of storing the materials, the importance of storage locations, and policies on storage procedures. Policies incentivising steel reuse and automated testing technology could help aid steel reuse further.

CHAPTER 4- DECONSTRUCTION AND LIFE CYCLE ASSESSMENT OF PITTSBURGH'S ENVIRONMENTAL CHARTER SCHOOL

WEIQING WANG, JASMIN CHIANG, ANLIN LI

EXECUTIVE SUMMARY

Demolition is to knock down buildings with heavy equipment whereas deconstruction involves systematic removal of reusable material. However, stakeholders often wonder whether the benefits are enough to justify the extra time and cost of the deconstruction process because of a lack of comparison data for the demolition and deconstruction process.[1] This paper aims to identify the gap between demolition and deconstruction through building life-cycle analysis (LCA) and comprehensive literature review. LCA can measure the environmental and economic impact of different building waste-management scenarios.[2] Most LCA scenario simulations use whole building assessment which often led to an impression of a binary decision option of choosing either deconstruction or demolition. This may result in the stakeholder's reluctance to integrate deconstruction into their practices.[3] This paper used the Environmental Charter School in Pittsburgh as a case-study to explore selective deconstruction opportunities via material optimization. The study set up three EOL scenarios of the school to break down the gap between demolition and deconstruction. This analysis intends to identify the reduction potential for the deconstruction of different building assemblies and to provide stakeholders with feasible deconstruction alternatives to make informed decisions. The finding indicated that an optimized deconstruction process could reduce approximately 50% of greenhouse gas (GHG) emissions compared to full building demolition. In such a case, structural materials such as steel and concrete have the highest GHG reduction potential. The result indicated the importance of reusing steel as an effective measure of circular building practices. Stakeholders should be more conscious in selecting more circular materials and incorporate design-for-deconstruction (DFD) methods in early design phases to ensure the reusability of building components.

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[1] Stephanie Boyd, Charley Stevenson, and JJ Augenbraun.(2012).Deconstructing Deconstruction: Is a Ton of Material Worth a Ton of Work?. Mary Ann Liebert, INC. Vol. 5 No. 6 December 2012 , DOI: 10.1089/sus.2012.9910

[2] Eva Queheille, Anne Ventura, Nadia Saiyouri and Franck Taillandier.(2022). A Life Cycle Assessment model of End-of-life scenarios for building deconstruction and waste management. Journal of Cleaner Production 339,130694.

[3] Hossain, M. U., Ng, S. T., Antwi-Afari, P., & Amor, B. (2020). Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. Renewable and Sustainable Energy Reviews, 130, 109948.

INTRODUCTION

The current solid waste management system in the US results in high costs to the environment, public health, and social equity.[4] In order to decrease these costs, the United States must move from a linear economic system towards a more sustainable circular economy model. If stakeholders salvage deconstructed components, it will relieve landfill burdens. This will retain the embodied energy and carbon in reclaimed materials and thereby reduce environmental impacts and energy consumptions.[5] In a circular economy, buildings will be perceived as material banks. Building owners can retain the component values of buildings for future urban-mining activities.[6] Unfortunately, most buildings are not designed to retain material value when they are disassembled due to the perception of increased construction costs. The intensive labor and economic cost often deterred building materials from being retained in the circular market at the EOL stage of the building. In the United States, 600 million tons of C&D (construction and demolition) debris, including buildings and infrastructure waste, were generated in 2018.[7] In which more than 90 percent of them are demolition waste. However, the potential material value and environmental benefits of deconstruction projects could be difficult to assess. The lack of such data prevents the stakeholders from fully understanding the impact and potential of the building's EOL stage. As a result, material value continues to dissipate in the current construction waste management system. To address the issue of wasted material reuse opportunity, this paper used LCA analysis to propose a more circular material management approach for the stakeholders to reconsider the EOL options of their buildings. The study intended to explore the carbon reduction potential by deconstructing different building assemblies to help with the decision-making process towards a circular economy. LCA simulation studies were conducted based on three major EOL scenarios of the Environmental Charter High School (ECS) in Pittsburgh.

In November of 2007, a small group of inspired parents and community leaders founded Environmental Charter School (ECS) by submitting a charter application which was approved in late spring 2008. Celebrating a decade in Pittsburgh, ECS continues to be a high demand school in the city, with a waiting list of over 650 students annually. Currently, ECS consists of three buildings that house grades K-8, but is planning a fourth location that will offer 9-12 grades, which is the case project for this study. This project is currently in the design phase and construction is expected to start in 2023. As compared with ECS's other properties, the new building will feature a broader array of sustainable systems and capabilities to support students' environmental education.[8] ECS is unique as compared with public school alternatives, but also stands apart from other charter schools in its focus on environmental responsibility. When completed, the

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[4] World Bank. (2022). Transitioning to a Circular Economy: An Evaluation of the World Bank Group's Support for Municipal Solid Waste Management (2010–20). Independent Evaluation Group. Washington, DC: World Bank.

[5] Ellen MacArthur Foundation. (2015) Delivering the Circular Economy: a Tool Kit for Policymakers:Construction and Real Estate. EMF, Cowes, UK.

[6] Mohit Arora et al. (2020).Resources, Conservation and Recycling Volume 154, March 2020,104581.

[7] EPA.Construction and Demolition Debris: Material-Specific Data. December 21, 2021,.https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/construction-and-demolition-debris-material C&D table graph, .

[8] About ECS. https://ecspgh.org/about-ecs.

building's design and operations will make a significant contribution to Sustainable Pittsburgh's CEOs for Sustainability Leading Forward campaign, specifically by helping to reduce carbon emissions across the region. Systems and curricula will be integrated to monitor, assess, adjust, and report on energy consumption, carbon emissions, water use, air quality, and other sustainable performance metrics. Attention to and transparent reporting of resource waste and usage provides a compelling example of environmental responsibility to other schools and organizations in the region who seek to improve their impact.[9]

Based on the above characteristics, ECS high school project is a perfect fit to conduct our case study because it has a need for flexibility and has ambitious sustainability goals. The need for flexibility is ideal to design spaces adaptively at the beginning and take circularity into consideration. Their ambitious sustainability goals align with the intention of improving material circularity in this paper. This study can help the school to better achieve the goal of decarbonization with maximization of resources input in the early design phase of the project. The goal of this paper is to provide school stakeholders with feasible deconstruction alternatives to make informed decisions in the early building design phase such as selecting more circular building materials and integrating DFD methods to facilitate future deconstruction activities.

Pittsburgh's Environmental Charter High School project is a perfect fit to conduct our case study because it has a need for flexibility and has ambitious sustainability goals.

LITERATURE REVIEW

Life cycle assessment (LCA) is a method for evaluating a product's or system's potential environmental impacts by taking into account all environmental exchanges (emissions, reagent and energy consumption) throughout the product's or system's entire life cycle for several so-called "impact categories," such as potential for global warming, resource depletion, and toxicity, etc.[10] In essence, LCA studies assist in avoiding solving one environmental issue while causing others: When you lessen the environmental impact at one stage of the life cycle only to enhance it at another, this unfavorable "shifting of loads" occurs. In the building industry, LCA has long been used extensively to establish load balances at all stages of the building life cycle and to quantify the interaction between buildings and the environment and is increasingly used as a decision support tool for all levels of the built environment, including materials, systems, whole buildings and communities.[11] In particular, LCA has been widely used to measure the environmental impact of different building waste-management scenarios.[12] Current LCA literature findings on demolition and deconstruction provides much evidence that

[9] What makes ECS different? https://ecspgh.org/high-school.https://ecspgh.org/high-school.

[10] C.H. Walker. "Book Review: Environmental Assessment of Products Chapman and Hall, London Volume 1 Methodology, Tools, and Case Studies in Product Development (1997) M. Hauschild and H. Wenzel (eds) Volume 2 Scientific Background (1998) H. Wenzel, M. Hauschild and L. Alting (eds) Vol 1 ISBN 0 412 80800 5, US$150.50, 544pp Vol 2 ISBN 0 412 80810 2, US$150.50, 566pp." Ecotoxicology. New York: Springer Nature B.V, 1999.

[11] Saade, Marcella Ruschi Mendes, Geoffrey Guest, and Ben Amor. "Comparative Whole Building LCAs: How Far Are Our Expectations from the Documented Evidence?" Building and environment 167 (2020): 106449–.

[12] Eva Queheille, Anne Ventura, Nadia Saiyouri and Franck Taillandier.(2022). A Life Cycle Assessment model of End-of-life scenarios for building deconstruction and waste management. Journal of Cleaner Production 339,130694.

This study includes lifecycle considerations for deconstruction, comparative analysis of impact reduction potential, and lifecycle considerations for educational buildings.

supports the environmental benefits of deconstruction.[13] Although LCAs were commonly used to quantify the benefits of building deconstruction over demolition, the majority of research conducted LCA on whole building analysis. This approach lacks practical solutions for stakeholders to incorporate deconstruction practices. To address such an issue, this paper concerns three particular themes of LCA studies including lifecycle considerations for deconstruction, comparative analysis of impact reduction potential and lifecycle considerations for educational buildings.

LCA and Deconstruction

LCA studies on deconstruction scenario simulations provided the framework of grouping building assemblies based on its material systems. Assefa and Ambler used different building scenarios for comparative LCA study to measure the impact of deconstruction for different building components.[14] Boyd et al. calculated the difference of cost and GHG emission of deconstruction and demolition on a wooden frame structure. This study aimed to answer the question 'is a ton of material worth a ton of work?' in project deconstruction. In addition to understanding the buildings' life-cycle considerations, other LCA studies focused on GHG reduction potential. Basbagill et al. used sensitivity analysis to identify the impact reduction potential of each building material.[15] In addition to understanding the buildings' life-cycle considerations, other LCA studies focused on GHG reduction potential. Basbagill et al used sensitivity analysis to identify the impact reduction potential of each building material.[16] While Gruescu and Menet measured the environmental footprint of different wall assemblies.[17] Both studies inspired the building system framework adopted in this paper.

LCA and Educational Buildings

A charter school is an alternative to traditional public schools. They are publicly funded but are privately operated by independent groups. As a result, charter schools do not have to follow the same regulations as public schools. They have more flexibility when it comes to curriculum, school hours, budget, and operations. However, with this freedom comes accountability; charter schools must deliver academic results. Likewise, charter schools are not assured of their enrollment. Unlike traditional public schools, students are not assigned to charter schools based upon home address. Instead, parents must proactively apply to and secure a spot for their child at the desired charter school.

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[13] David Cheshire.(2016).Building Revolutions:Applying the Circular Economy to the Built Environment. RIBA Publishing.

[14] G.Assefa, C.Ambler. (2016). To demolish or not to demolish:Lifecycle Consideration Of repurposing buildings. Sustainable Cities and Society 28 (2017)146–153.

[15] S.Boyd et al. (2012). Deconstructing Deconstruction:Is a Ton of Material Worth a Ton of Work?. Mary Ann Libert Inc. DOI: 10.1089/sus.2012.9910.

[16] Basbagill et al. (2012).Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts . Building and Environment 60 (2013) 81e92.

[17] I.C.Gruescu, J.Menet. (2012). Environmental footprint of a wall assembly by life cycle assessment. Proceedings 2nd LCA Conference, 6-7 November 2012, Lille France.

In Pittsburgh, 14.5% of public-school students attended charter schools in 2022. The annual closing rate of charter schools in Pennsylvania is 1.3%, which falls at the lower range compared to other locations within the US.[18] Data showed that while the enrollment rate in public schools are declining, the enrollment rates for charter schools are steadily increasing. It indicates the demand of a more innovative pedagogy among parents and students.[19] In terms of the architectural program, And Thi Hoai Le et al did a thorough literature review of the sustainable refurbishment factors for school buildings.[20] On the other hand, L.Rasmussen analyzed how educational pedagogies affected the spatial configuration of teaching spaces.[21] The two papers examined the relationship between educational pedagogy and building life-cycle considerations. This information contributed to setting up the scenarios for LCA analysis in this study.

PROBLEM STATEMENT & RESEARCH QUESTIONS

As stated before, lack of information related to more detailed and connected benefits and costs of circular approaches like deconstruction has become one of the biggest challenges that cause stakeholder's reluctance to embrace this new mode and integrate it into their practices. This obvious gap can be further broken down into the following sub-problems.

1. Environmental impacts: Whether applying a circular approach like deconstruction will generate less environmental impacts than the traditional end-of-life approach, like demolition, remains unclear. Although recycling C&D waste adds value to the traditional linear economy, it requires other resource inputs and stakeholder's efforts to realize the changes. It is possible that the deconstruction process can produce extra impacts, so figuring out the environmental impacts is important for decision making and is beneficial to design an environmentally friendly deconstruction strategy.
2. Material reuse value: Understanding what material is worth salvaging at the end-of-life stage is critical for all stakeholders, especially for the contractors who have the closest connection with building components. This enables them to target the most valuable materials and make full use of inputs for recycling and reusing.

The above problems naturally become our research questions. What are the environmental impacts of conducting deconstruction for a construction project? Which materials have the highest reuse value?

Research questions:

What are the environmental impacts of conducting deconstruction for a construction project?

Which materials have the highest reuse value?

[18] National Alliance for Public Charter Schools, The Health of the Public Charter School Movement: A State-by-State Analysis. (2015) of individual state education departments and charter school organizations

[19] Pittsburgh Public School Enrollment Summary.(2022)

[20] An Thi Hoai Le et al. (2018). Sustainable refurbishment for school buildings: a literature review. International Journal of Building Pathology and Adaptation Vol. 39 No. 1, 2021, p. 5-19. DOI 10.1108/IJBPA-01-2018-0009.

[21] L.Rasmussen. (2021).Building Pedagogies. A historical study of teachers' spatial work in new school architecture. Education Inquiry. 2021, Vol.12, No.3, p.225–248.

What will be the economic feasibility including benefits and costs of applying this kind of circular approach in a project?

We wish to start with an example project and obtain information and data closely related with the stakeholders and the project. A better understanding of deconstruction's advantages and disadvantages over the traditional demolition can be established from the analysis of gained information and data. By doing so, stakeholders can have more references and feel more confident when making their decisions for transition to a more circular mode.

METHODOLOGY

The method behind the tool used in this study is life cycle assessment (LCA). In this project, LCA simulations are conducted for three major end-of-life scenarios tailored for the case educational facility project considering its organizational background and pursuit in building sustainably. The baseline scenario (SC1), demolition, is the worst case where material selections are with the current design documents and no circular approach is applied into end-of-life processes. The best-case scenario (SC2), deconstruction, is the optimized setting where materials are processed with their full recycle or reuse potential. The last scenario (SC3) is created to evaluate the effectiveness of selective or partial deconstruction strategy. This is achieved by optimizing one building system's material selection and EOL process utilizing circular and sustainable thinking as one sub-scenario. By comparing the LCA results of the scenarios horizontally, the contribution of the circular strategies to the building's life cycle environmental impacts can be quantified.

Life cycle assessment (LCA) tool selection and workflow

The automated life cycle assessment platform, One Click LCA[22] is used to estimate potential environmental impacts during the deconstruction and demolition of the case building. It provides a whole LCA-related ecosystem that supports the assessment of impact, cost and material circularity on its platform. This LCA tool takes into account all life cycle phases, including resource extraction, building construction, building assembly, maintenance, repair, and disposal. This tool's strength is its high level of connectivity with other applications, including Excel and BIM (Building Information Modeling), which enables direct data importation from them. The specific calculation model used for this study is the embedded LEED compliant calculation framework in One Click LCA. The impact indicators measured in this study are stated in **Table 4.1.**

[22] https://www.oneclicklca.com/

Table 4.1: Environmental impact category description

Impact category	Unit(s)	Description
Global warming potential	$kgCO_2$ eq	Describes changes in local, regional, or global surface temperatures caused by an increased concentration of greenhouse gasses in the atmosphere. Greenhouse gas emissions from fossil fuel burning are strongly correlated with acidification & smog. Called “carbon footprint”.
Acidification potential	$kgSO_2$ eq	Describes the acidifying effect of substances in the environment. Substances such as carbon dioxide dissolve readily in water, increasing the acidity and leading to damage to water ecosystems.
Eutrophication potential	KgN eq	Describes the effect of adding mineral nutrients to soil or water, which causes certain species to dominate an ecosystem, compromising the survival of other species and sometimes resulting in die-off of entire animal populations.
Depletion of nonrenewable energy	MJ	Describes the depletion of fossil fuel in the life-cycle of the building

Scenario Settings

More than a quarter of charter schools closed after five years of operation, and about half shuttered after 15 years, according to an analysis on charter school closures between 1999 and 2017 published by Network for Public Education.[23] Given the high bankruptcy rate of charter schools, we developed four end-stage scenarios based on the assumption that charter schools will be closed, repurposed, or rebuilt after 15 years.

The case building in this research, Environmental Charter School's academic building has 4 stories and is approximately 65,292 square feet. Major functional areas include classrooms, laboratories, staff rooms, kitchens, and other shared areas. Further assembly details about the building are provided in **Table 4.2.**

[23] Burris, Carol, and Ryan Pfleger. “Broken Promises: An Analysis of Charter School Closures from 1999-2017.” Network for Public Education. Network for Public Education. 225 East 36th Street, Apartment 10-O, New York City, New York 10016. Tel: 646-678-4477; e-mail: info@networkforpubliceducation.org; Web site: https://networkforpubliceducation.org/, November 30, 2019. https://eric.ed.gov/?id=ED616256.

Table 4.2: Assembly Details

Assembly	
Structure	Steel-framed structure
Floor Slab	Reinforced concrete, EPS insulation
Exterior Wall	Precast concrete wall elements, Gypsum board, Metal panel, Mineral wool Insulation
Roofing	Glass with reflective coating, wooden frame
Interior Finishing	Poured Concrete, Aluminum facade, hot rolled plate, XPS insulation (extruded polystyrene), Polyiso (PIR) insulation board
Total Floor Area	Tile, Resilient flooring, Acoustic panel.etc.

These scenario settings are based on data representative of the general condition of charter schools in the Pittsburgh School District.

Scenario 1: Demolition (15 yrs.)

In this scenario, after the charter school is closed the school building will be completely demolished and a new building will go up on the same site. It is the typical scenario at most building's end-of-life and is perceived as the most 'cost-efficient' method by many owners. For LCA, we assume the end-of-life of all materials to be landfilling or incineration.

Scenario 2: Optimal Deconstruction (15 yrs.)

In this scenario, several end uses (recycling, reuse, burning or landfill) were selected for each building component based on material properties and historical use experience. This is the most idealized scenario with the goal of minimizing the environmental impact. If a material can be recycled or reused, we adapt its end-of-life process to the most decarbonized option, while materials that cannot be reused or recycled will be disposed of in landfills or incinerated.

Scenario 3: Material optimization of building systems

This scenario is an improvement based on scenario 2. By changing materials from the current selections to more environment-friendly combinations for one building system at a time and then comparing the results, we can find the optimized materials and identify the efficiency of the optimization strategy for each system.

Findings derived from these simulations are expected to give stakeholders more information and thus create a range of feasible options. They can choose to improve some portions of the entire building and still make positive impacts.

The following iterations are simulated:

3a: Baseline Steel structure vs Proposed Steel structure

3b: Baseline Floor slab vs Proposed Floor slab

3c: Baseline Exterior wall vs Proposed Exterior wall

3d: Baseline Window vs Proposed Window

3e: Baseline Roof vs Proposed Roof

3f: Baseline Interior finishing vs Proposed Interior finishing

Scenario 3a: Deconstruction of Steel columns and beams

Steel components were the primary structural material used at ECS School, with a total of 465.64 tons used, including columns, beams and floor trim panels. Steel is a durable and long-lasting material, which makes it a good candidate for reuse. Unlike some other materials, steel does not decompose or degrade over time, so it can be used repeatedly without losing its strength or effectiveness. With this characteristic in mind, in optimization scenario 3a, it is assumed that all steel components can be reused in another project.

Scenario 3b: Deconstruction of Floor structure

Due to the material grouping system in One Click LCA, scenario 3b- floor structure only optimized the concrete in floor slabs. The steel components such as decking of the slabs were accounted for in Scenario 3a (steel structure). The concrete with the most circular EOL process was chosen for LCA simulation with 40%recycled binders in cement.

Scenario 3c: Deconstruction of Exterior walls

The exterior wall of ECS high school consisted of a cavity wall on the outer shell and a cold-formed metal framing (CFMF) system on the inner side. The outer shell components included concrete, wool insulation and concrete masonry unit (CMU). All three items were replaced with materials with the same properties but with a reused EOL process and less embodied carbon.

Scenario 3d: Deconstruction of Window:

Most windows in ECS schools are double glazed with reflective coatings and have wooden frames. Glass is typically more difficult to reuse than other materials such as steel and tile because it is brittle and easily fractured or damaged. This can make it difficult to transport and handle, especially if it has been reused. In scenario 3d, all glass is set to be recycled rather than reused, and the wooden window frames are landfilled.

Scenario 3e: Deconstruction of Roof

The roofing system consists of concrete, hot rolled aluminum panels, and roof insulation. In Scenario 3e, the original concrete was replaced with concrete that contains a high percentage of fly ash, the hot rolled aluminum panels were replaced with steel, and all other components were assumed to be reused.

Scenario 3f: Deconstruction of Interior finishing

Interior finishing in the ECS school included materials such as tile, acoustic wall panels, resilient flooring, carpet, stair terrazzo, fiber-glass reinforced paneling and carpet. In scenario 3f, certain materials such as fiber-glass reinforced paneling with little reuse potential were replaced by acoustic wall paneling with a more circular EOL process. The substitution was confirmed through design drawings to ensure the replacement will serve the same function. All other materials in scenario 3f were assumed to be reusable at the EOL stage.

Detailed end-of-life selections for each scenario are provided in **Table 4.3.**

Table 4.3: End of life selection for each scenario

<table>
<tr><th>Assembly</th><th>Sc1 Demolition</th><th>Sc2 Deconstruct-ion</th><th>Sc3-a Column and Beam</th><th>Sc3-b Floor</th><th>Sc3-c Exterior Wall</th><th>Sc3-d Window</th><th>Sc3-e Roof</th><th>Sc3-f Interior Finishing</th></tr>
<tr><td>COLUMN AND BEAM</td><td rowspan="6">Recycle steel, concrete</td><td rowspan="3">Reuse Steel</td><td rowspan="3">Reuse Steel</td><td rowspan="3">Recycle steel</td><td rowspan="6">Recycle steel, concrete</td><td rowspan="6">Recycle steel, concrete</td><td rowspan="6">Recycle steel, concrete</td><td rowspan="6">Recycle steel, concrete</td></tr>
<tr><td>Supported area(ft²)</td></tr>
<tr><td>Intermediate floors area (ft²)</td></tr>
<tr><td>FLOOR</td><td rowspan="2">Reuse steel</td><td rowspan="3">Recycle steel, concrete</td><td rowspan="2">Reuse steel</td></tr>
<tr><td>Steel stud framing(ft²)</td></tr>
<tr><td>Concrete(ft²)</td><td>Recycle concrete</td><td>Recycle concrete</td></tr>
<tr><td>EXTERIOR WALL</td><td rowspan="21">Landfill</td><td rowspan="4">Reuse brick, metal panel, CFMF</td><td rowspan="21">Landfill</td><td rowspan="21">Landfill</td><td rowspan="4">Reuse brick, metal panel, CFMF</td><td rowspan="4">Landfill</td><td rowspan="8">Landfill</td><td rowspan="12">Landfill</td></tr>
<tr><td>Brick (ft²)</td></tr>
<tr><td>Metal panels(ft²)</td></tr>
<tr><td>CFMF (ft²)</td></tr>
<tr><td>WINDOW</td><td rowspan="3">Recycle glazing, aluminum frame</td><td rowspan="17">Landfill</td><td rowspan="3">Recycle glazing, aluminu m frame</td></tr>
<tr><td>Aluminum framed(ft²)</td></tr>
<tr><td>Glazing(ft²)</td></tr>
<tr><td>Wooden cladding(ft²)</td><td>Landfill</td><td rowspan="14">Landfill</td></tr>
<tr><td>ROOF</td><td rowspan="3">Recycle concrete, metal</td><td rowspan="3">Recycle concrete , metal</td></tr>
<tr><td>Suspended concrete slab(ft²)</td></tr>
<tr><td>Metal sheeting(ft²)</td></tr>
<tr><td>Insulation boards(ft²)</td><td>Reuse</td><td>Reuse</td></tr>
<tr><td>INTERIOR FINISHING</td><td rowspan="8">Reuse</td><td rowspan="9">Landfill</td><td rowspan="8">Reuse</td></tr>
<tr><td>Furniture</td></tr>
<tr><td>Acoustical ceiling panel (ft²)</td></tr>
<tr><td>Carpet (ft²)</td></tr>
<tr><td>Acoustical wall panel (ft²)</td></tr>
<tr><td>Tile (ft²)</td></tr>
<tr><td>Resilient flooring (ft²)</td></tr>
<tr><td>Terrazzo-Stair (ft²)</td></tr>
<tr><td>Fiberglass reinforced paneling (ft²)</td><td>Recycle</td><td>Recycle</td></tr>
</table>

FINDINGS

Finding1: Deconstruction can balance the dominance of material related emissions in life cycle environmental impacts

By comparing the CO2 emissions by life cycle stages for all scenarios, it is found that the emissions from materials contribute nearly 80% of the total emissions (**Figure 4.1**). This fact further demonstrates the importance of prioritizing material related activities to decarbonize a building learned from the upfront literature reviews.

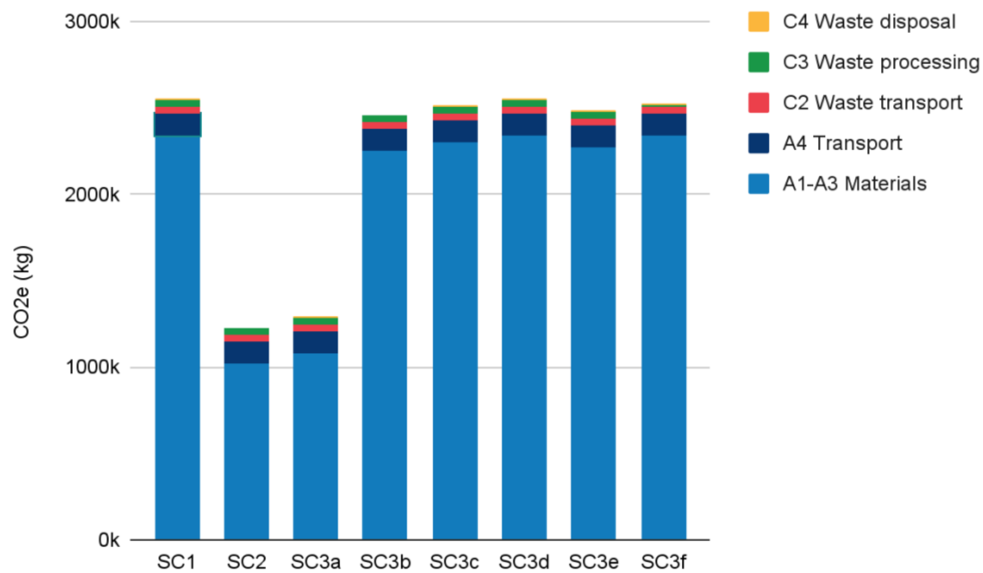

Figure 4.1: Carbon emission by Life-cycle stages for different scenarios

The proportion of different life-cycle stages emissions does not change much in different scenarios. However, with deconstruction, the dominance of emissions from materials can be balanced where other stages create more impacts. A1-A3 emissions take up 89% of the total emission in the worst-case scenario 1, which is the traditional demolition. This percentage drops down to 72% in the best case of optimal deconstruction scenario 2 while other down-stream stages like waste management have more impacts.

The contribution of different building systems to the entire emission is also worth analyzing. After organizing the results generated by One Click, it is found that beams, floors and roofs are the largest contributors for all impact categories in the complete demolition (**Table 4.4**), which is nearly 80% in all impact indicators.

Table 4.4: Percentage contribution of different building elements for the impact categories in Scenario 1

Assembly	Global warming (kg CO2)	Acidification (kg SO2)	Eutrophication (kg N)	Depletion of nonrenewable energy (MJ)
Foundation and footings	3.17%	2.50%	2.09%	3.30%
External walls and facade	12.82%	15.22%	8.16%	11.83%
Internal walls	1.15 %	1.65%	1.17%	1.20%
Beams, floors and roofs	80.86 %	77.63%	88.18%	78.90%
Windows and doors	1.94 %	2.92%	0.37%	4.64%
Interior finishing	0.06 %	0.08%	0.03%	0.13%

In the optimal deconstruction scenario, Scenario 2, a similar pattern of contribution is observed where different building components contribute to varying degrees (**Table 4.5**). Beams, floors and roofs are still the main contributors for the environmental impacts in the deconstruction setting but their impacts are reduced by a fair amount through optimizing their end-of-life treatments, which is at least a 35% reduction.

Table 4.5: Percentage contribution of different building elements for the impact categories in Scenario 2

Assembly	Global warming (kg CO2)	Acidification (kg SO2)	Eutrophication (kg N)	Depletion of nonrenewable energy (MJ)
Foundation and footings	10.32%	9.59%	18.15%	19.92%
External walls and facade	31.45%	33.05%	35.35%	32.81%
Internal walls	5.01%	5.92%	8.62%	5.10%
Beams, floors and roofs	45.33%	39.23%	34.33%	29.52%
Windows and doors	15.65%	19.64%	18.62%	30.11%
Interior finishing	2.56%	2.16%	3.08%	2.46%

Finding 2: Optimal deconstruction can reduce GWP for over 50%

According to the LCA results, scenario 1 has a CO_2 consumption rate of 27.54 kg CO2e/m^2/year, and the social cost of carbon is $132,736.

The cradle to grave embodied carbon result is shown in Figure 4.2 of the Carbon Heroes Benchmark in One Click, which measures the level of a building's embodied carbon for a fixed 60-year life cycle in One Click's USA typical building database. This shows that without taking any circular strategy into design, the embodied carbon of the case building is at level C.

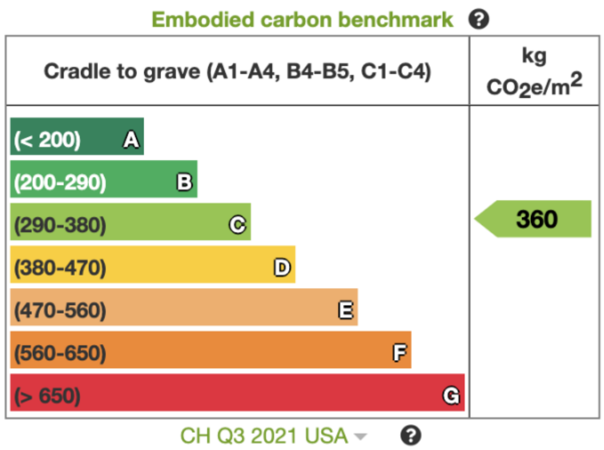

Figure 4.2: SC1 result for Carbon Heroes Benchmark

The change in EOL brings a significant reduction in environmental impact. LCA results show that the CO2 consumption rate for scenario 2 was reduced to 13.28 CO2e/m^2/year and the social cost of carbon is $64,002. Based on the Carbon Heroes Benchmark, the embodied carbon impact in Scenario 2 is assessed at Level A (Figure 4.3).

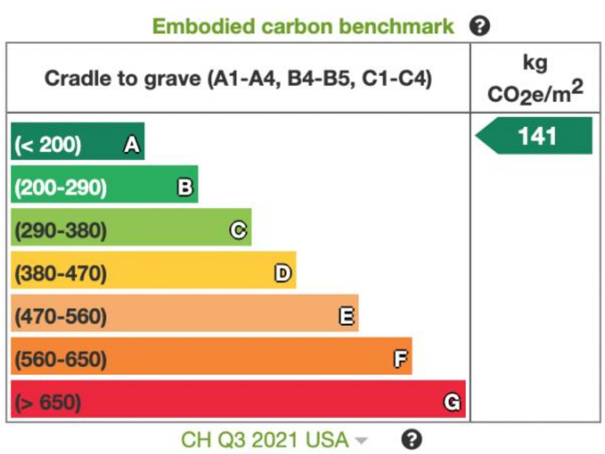

Figure 4.3: SC2 result for Carbon Heroes Benchmark

When comparing the results of all impact indicators for the base case scenario of demolition (SC1) and the optimized deconstruction scenario (SC2), all impact categories are decreased by adopting a more circular end-of-life material process (Figure x). It avoids 1,321,798 kg of CO_2 eq of Global Warming Potential compared to a scenario with complete demolition, which equals to about 4-year CO_2 emissions generated by consuming the needed electricity of this building[1]. For Acidification, the impact produced by deconstruction is 42.3% of the impact of demolition. Eutrophication impact gains the best improvement by the optimized deconstruction among the four indicators, which is 13.3% of the emission of demolition. Comparison is visualized in **Figure 4.4**. The values are shown as a percentage of Scenario 1. It depicts the relative impacts of each scenario and allows all impact categories to be examined simultaneously as each has a different unit of measure.

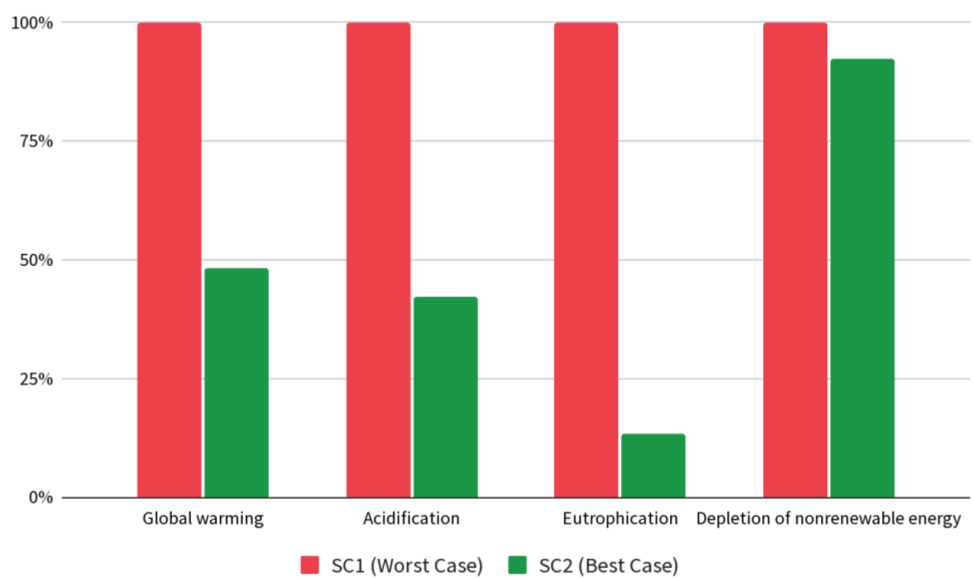

Figure 4.4: Impact assessment results of SC1 and SC2 relative to SC1

Finding 3: Apply selective deconstruction to column and beam assemblies can reduce environmental impacts mostly

To figure out how much each building assembly can contribute to the at least 50% reduction from the worst case to the best case discussed above, the selective deconstruction scenario 3 simulations are conducted. Comparing the best-case results (SC2) with the results of deconstruction for columns and beams (SC3a), we can conclude that the majority of reduction results from optimizing columns and beams. This is because this assembly is steel intensive. Reusing steel can bring the most benefits to the environment for a steel frame building as the case project.

[1] This is calculated based on the energy simulation result of this building provided by AUROS Group using EPA GHG Calculator. https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references.

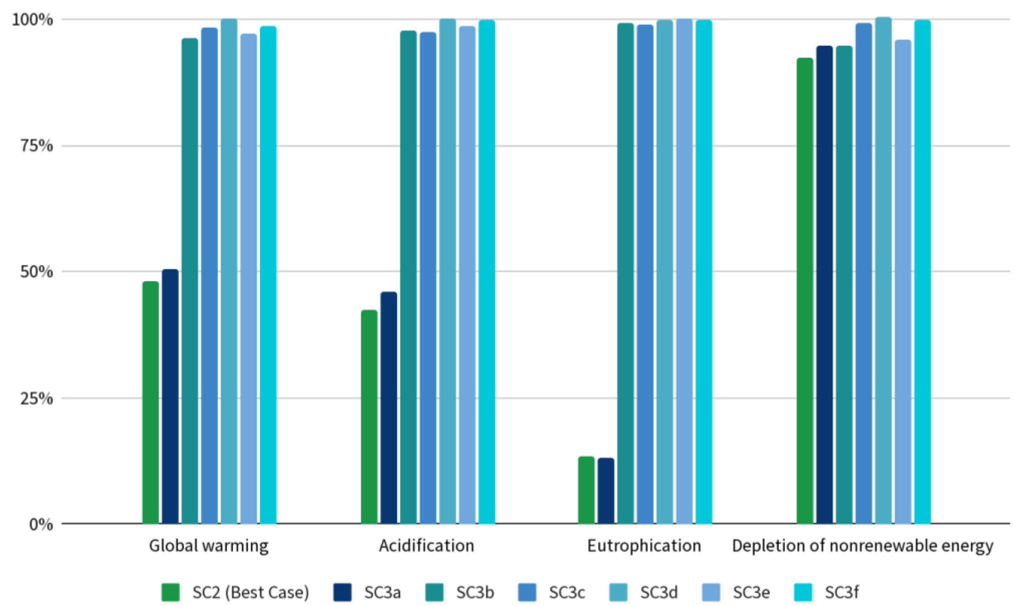

Figure 4.5: Impact assessment results of SC3 relative to SC1

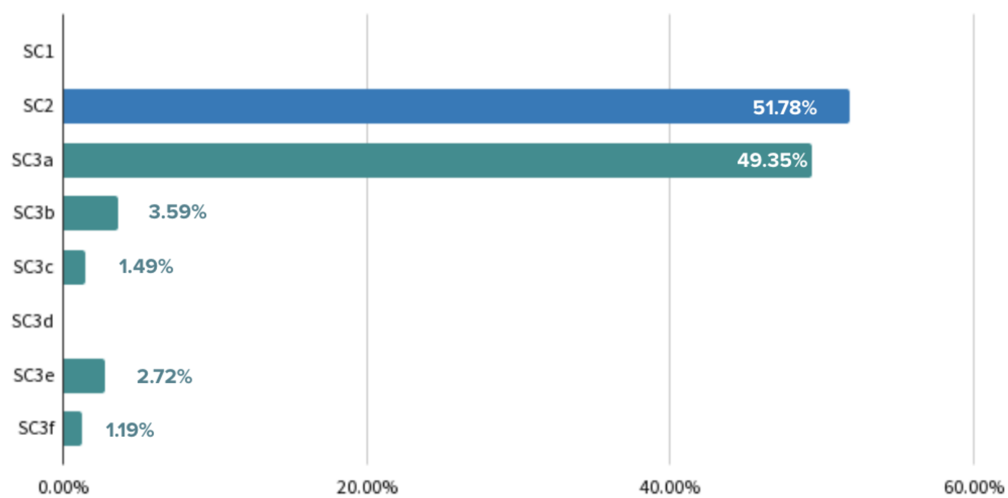

Figure 4.6: GWP reduction (%)

Taking a closer look at the most concerning indicator of global warming potential, employing circularity thinking in columns and beams can bring the most benefit, which is nearly a 50% reduction (**Figure 4.6**). Optimizing floor and roof assemblies are the most impactful among other building systems. It is also worth mentioning that applying circular deconstruction strategy does not reduce the environmental impacts of window assemblies. Materials used in window assembly are a relatively small number compared to other assemblies' usage. The efforts and resources invested in deconstructing them can produce more emissions than just sending them to the landfill. Another reason why this happens to window assembly may be that the current design's material selection is already quite sustainable which leaves not much space for improvement.

DISCUSSION

This study investigates the prospects for deconstruction through life cycle assessment and material optimization. The results of this study suggest that salvaging deconstructed components will not only reduce the burden on landfills, but also retain the embodied energy and carbon in the recycled material. Therefore, it will reduce the environmental impact and energy consumption.

In contrast to previous studies that only provided a binary conclusion of demolition or deconstruction, this study explores the idea of selective deconstruction. As a compromise, selective deconstruction gives contractors and developers the option to weigh the environmental impact against the additional burden of deconstruction, providing them with more options when considering the end-of-life of a facility. Moreover, by replacing original materials from a design for deconstruction (DFD) perspective, we investigate the potential for reuse/recycle of typical construction materials, offering insights into maximizing material value while lowering deconstruction expenses for the best option. Overall, this study provides valuable insights into the circular EOL methods of educational buildings, helping stakeholders understand material recyclability and strategies of systematic deconstruction.

Recommendations

With the constantly changing pedagogy and educational policy, it has become harder to predict the operational expectancy of an educational facility. For charter schools where there are more uncertainties. Therefore, it is crucial for school stakeholders to think about and prepare for the end-of-life scenarios for their buildings. Based on the result of the sensitivity analysis of different deconstruction scenarios, this paper provided stakeholders with two recommendations:

1. To use more circular materials in building design. Where the materials are more durable, have less embodied carbon and could be easily maintained. By retaining the utmost value of each building component, one can increase the overall reusability of each building system and effectively reduce GHG emission.
2. To incorporate DFD measures in building design. Obviously, due to the extended lifespan of buildings, there is an inherent challenge in projecting use type changes over their lifetime. However, it is advisable for designers and developers to plan for future changes in the use of new constructions. The study shows the drastic reduction of GHG emission by reusing steel components. DFD practices for steel frame design such as disassemble connection design and modular components are all practical measures that could be incorporated in early design phases without noticeable extra cost to the project.

The two recommendations could serve as high-level design principles for educational facility stakeholders to prioritize feasible deconstruction strategies at the EOL stage of their buildings.

Limitations & Future Work

Despite its novelty, this study has some limitations. First, because the evaluation relied solely on Oneclick software, our LCA procedure was significantly reliant on the software's calculation technique and prototype data. Second, we were unable to incorporate precise building components from the design documents into the model due to the material library's limitations, which may have resulted in an underestimate of the total environmental impact. Last, our assumptions concerning end-of-life building components are fairly ideal, as we expect that materials labeled for recycling or reuse will finally enter the recycling market or be reused. In actuality, the environmental effects of deconstruction may be greater than we assumed in Scenario 2.

To supplement these limitations, three next research directions are established. To begin with, future research should consider the use of different software for LCA to eliminate limitations due to the software's built-in algorithms and database. Second, it is critical to investigate the life cycle cost-effectiveness of deconstructing educational facilities to provide an optimal recommendation that integrates the balance of environmental advantages and cost control. Last, given the short lifespan of charter schools, research on charter school repurposing can be combined with this research to enhance its realistic value and help provide targeted recommendations to stakeholders of such educational facilities.

CHAPTER 5- POLICY OPTIONS FOR IMPLEMENTING A CIRCULAR ECONOMY IN PITTSBURGH'S CONSTRUCTION INDUSTRY

AISHWARYA SINGH, BHAVIKA KOYA, SERAH KALLERACKAL

CHAPTER SUMMARY

Construction is a resource-intensive industry where a Circular Economy (CE) is essential to minimize global impacts and conserve natural resources. According to the United States Environmental Protection Agency, in 2018, the U.S. produced 600 million tons of C&D debris, which is more than twice as much produced in terms of municipal solid waste. CE is an emerging concept that promotes long-term sustainability by creating material loops that circulate along critical supply chains. Circular building design involves strategies such as design for disassembly (DfD) to allow future repair, remanufacturing, reuse of building components, building adaptive reuse, deconstructing, and salvaged material usage in new construction. However, uncertainties caused by fluctuating raw material prices, scarcity of materials, increasing demand, consumers' expectations, lack of proper waste infrastructure, and improper recycling technologies and practices all lead to complexities in the construction industry. Research has identified several critical barriers to implementing CE that include financial constraints for innovation, an underdeveloped market for salvaged materials, a lack of stakeholders' knowledge and awareness of CE strategies, and the competitive and fragmented nature of the construction sector. Fiscal and regulatory incentives were identified as enablers to address these barriers, and the participation of stakeholders has been discussed in terms of implementing these incentives.

This study is aimed to support the transition to a circular economy by generating a policy-supported framework that construction industry stakeholders in Pittsburgh can adopt. Our findings are based on a review of the existing literature, interviews with industry professionals who are leading small-scale circular economy efforts in Pittsburgh, and international case studies and policy reviews. The interviews with local industry professionals helped us recognize the lack of CE catalysts and initiatives integrated at a municipality scale that can incentivize stakeholders to design, implement, and apply CE principles. Case studies were used to explore how policies and pilot projects are incentivized in countries in Europe.

The results from our research helped to identify the similarities and differences between industries in the US and other countries to arrive at CE policy recommendations. Therefore, our CE framework draws from existing policies in Pittsburgh, international

policies and their local context applicability, and CE material innovations that are supported by local government and stakeholder incentives. This study focused on relating all the findings to the Pittsburgh context and framing a robust recommendation for a policy toolkit.

INTRODUCTION

According to the MacArthur Foundation, the construction industry practices a non-sustainable, linear economic model, based on the idea of "take, make, dispose of".[2] This linear model does not support building elements being deconstructed and reused, as they become obsolete at the end-of-life of the building. This linear model assumes that natural resources are abundant, but now the world is exceeding its planetary boundaries, highlighting the need for a transition to a circular economy (CE).[3] The transition to CE requires a change in both attitudes and the core structure of all industries.[4] Much is already known about the drivers and barriers to implementing the changes. Drivers and barriers related to recycling C&D waste have been presented by Williams (2020)[5], Wahlström et al., (2020)[6] and previous European Union (EU) funded projects (EU HISER[7]; EU IRCOW[8]). More knowledge on how companies can be supported in practice is required to accelerate the transition to CE in the construction sector. There is little literature on how companies, agencies, and public and private organizations with a CE business model benefit from the current policy framework and which policy instruments are viewed as drivers for advancing their activities. As governments and industries around the globe move towards a CE, it is critical to align ambitions and create common goals. Therefore, this study aims to understand the policy landscape and the role of policies in the transition toward a CE in the city of Pittsburgh.

More specifically, the five objectives of the study were (1) to benchmark the national and local CE policy framework in other countries and investigate whether the construction sector is addressed, (2) to build a database of policies and CE actors along the circular value chain in the construction sector in the US, (3) to review actors with CE goals and implementations to identify links to national and local policies, (4) to identify key drivers and barriers related to the successful implementation of CE in Pittsburgh, and finally (5) to recommend national and local CE policies that support the transition to a CE in the construction sector in practice in Pittsburgh.

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[2] Ellen MacArthur Foundation. Towards a Circular Economy: Business Rationale for an Accelerated Transition. Available online: https://www.ellenmacarthurfoundation.org/publications/towards-a-circular-economy-business-rationale-for-an-accelerated-transition (accessed on 26 May 2021).

[3] Wahlström, M.; Bergmans, J.; Teittinen, T.; Bachér, J.; Smeets, A.; Paduart, A. Construction and Demolition Waste: Challenges and Opportunities in a Circular Economy. Available online: https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-reports/construction-and-demolition-waste-challenges-and-opportunities-in-a-circular-eeconomy (accessed on 26 May 2021).

[4] Gillabel, J.; Manshoven, S.; Grossi, F.; Mortensen, L.F.; Coscieme, L. Business Models in a Circular Economy. Available online: https://www.eionet.europa.eu/etcs/etc-wmge/products/business-models-in-a-circular-economy (accessed on 28 May 2021).

[5] Williams, R.; Artola, I.; Beznea, A.; Nicholls, G. Emerging Challenges of Waste Management in Europe Limits of Recycling—Final Report. Available online: https://trinomics.eu/wp-content/uploads/2020/06/Trinomics-2020-Limits-of-Recycling.pdf (accessed on 26 May 2021).

[6] Wahlström, M.; Bergmans, J.; Teittinen, T.; Bachér, J.; Smeets, A.; Paduart, A. Construction and Demolition Waste: Challenges and Opportunities in a Circular Economy. Available online: https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-reports/construction-and-demolition-waste-challenges-and-opportunities-in-a-circular-economy (accessed on 26 May 2021).

[7] Hiser Project. Available online: http://hiserproject.eu/ (accessed on 26 May 2021).

[8] IRCOW Project. The IRCOW Project. Available online: https://www.europeandemolition.org/industry/projects/ircow (accessed on 26 May 2021).

LITERATURE REVIEW

The shift from a linear model of produce-use-dispose to a circular model of reduce-reuse-recycle is vital for the continuous growth and improvement of society and the planet. The circular economy is about keeping materials and resources in use and retaining their value, rather than consuming and disposing of them. To achieve this, products are designed to have longer lives, to be reused, remanufactured, or reassembled instead of discarded[9] but, more importantly, to learn to live harmoniously with our environment. As centers of human activity, cities are in a prime position to capitalize on the transition towards a circular economy,[10] the focus on devising solutions to the circular economy that can be applied by and for the city is essential to propel this movement forward.

The literature on circular economy has extensive research, solutions, and suggestions to guide cities. However, the momentum of the shift from linear to circular has to overcome the barriers of transition from principle to practice. In the transition to a more circular economy, monitoring the key trends and patterns is essential in understanding how the various elements of the circular economy are developing over time and recognizing the gaps. For example, the following are some of the gaps in the implementation of circularity in Spain.

***Funding gap*:** Cities and regions face constraints in terms of insufficient financial resources, financial risks, lack of critical scale for business and investments, and lack of private sector engagement.

***Regulatory gap*:** Inadequate regulatory framework and incoherent regulation across different levels of government represent a challenge for cities and regions.

***Policy gap*:** A lack of holistic vision is an obstacle for many cities and regions. This can be due to poor leadership and coordination. Other policy gaps concern the lack of political will.

***Awareness gap*:** Cultural barriers represent a challenge for many cities and regions along with a lack of awareness and inadequate information for policymakers to make decisions, businesses to innovate, and residents to embrace sustainable consumption patterns.

***Capacity gap*:** The lack of human resources is a challenge for cities and regions. Technical capacities should not just aim for optimizing linear systems but strive towards changing relations across value chains and preventing resource waste.[11]

According to Wijkman and von Weizsäcker, the hurdles to a circular economy are most closely related to shortcomings and failures in policy frameworks, not least the flawed incentives structure of the economy.[12] Policy gaps relate to the lack of leadership and coordination across municipal departments and different levels of government, which in turn undermine policy coherence. As the circular economy is systemic by nature, a cross-sectoral approach is needed to ensure that the city rethinks urban policies and their relationship with

The hurdles to a circular economy are most closely related to shortcomings and failures in policy frameworks, not least the flawed incentives structure of the economy.

[9] Cheshire, D. (2019). *Building Revolutions: Applying the Circular Economy to the Built Environment*. RIBA Publishing

[10] Gatheca, M. (2021, July 30).Final Report Baselining for a Circular Toronto. City of Toronto

[11] Organization for Economic Co-operation and Development. (2021). *The Circular Economy in Granada, Spain*. OECD Publishing

[12] Wijkman, A., & von Weizsäcker, E. (n.d.). *Reflections on Governance for a Circular Economy*. Global Challenges Foundation

resource efficiency holistically, beyond the optimization of the existing policies towards the achievement of targeted environmental goals.

The construction sector is an ideal industry for introducing a closed-loop economic model, which stands for the practice of sharing, reusing and recycling the generated waste. It is characterized by the high durability of products, the possibility of repairs and adjustments, as well as resale potential in the market. Features of buildings such as durability, the possibility of modernization, and reuse predispose them to apply circular concepts – closing economic loops so that the goods circulate as long as possible with simultaneous value maximization. According to Cutaia, repairs, real estate trade, and sharing or renting rooms have been taking place for hundreds of years and are all examples of applying the circular concept in real life.[13] However, the use of circular concepts occurs primarily at earlier stages of the life cycle of buildings, as usually it is difficult to follow a circular design concept on a structure designed for linear economy and the process will be non-optimized. The construction sector embeds a high potential for innovation and ample room for improvement. The regulatory, economic, and administrative strategies can be devised such that we can leverage the existing policies, by increasing the awareness of their existence among stakeholders.

Policy Development in the EU

It is essential to investigate the gap in policy and fiscal incentives at a national and international level in order to identify opportunities to supplement CE now and in the future. The EU's transition to a CE has reduced pressure on harnessing natural resources while creating jobs and sustainable economic growth. In December 2019, the Von der Leyen Commission[14] unveiled its European Green Deal, an ambitious plan to transform the EU's economy into a fair, sustainable, and prosperous one. The European Green Deal is a comprehensive growth agenda that aims to make Europe the first climate-neutral continent while attempting to ensure that no one is left behind in this transition. This deal is the result of an evolution in the European Commission's thinking and of a series of policy developments across different areas since 2011. Therefore, it is important to reflect back specifically on the steps which the European Commission took to take a lead in circular economy policies globally. From an initial aim of improving resource efficiency to redefining growth with positive social, environmental, and economic benefits, this report seeks to analyze the EU policy-making process.

Deconstruction Policy in the U.S.

Deconstruction, is construction in reverse, the ability to dismantle buildings part by part while avoiding damage, in anticipation of maintaining the value by reuse in different contexts.

In the United States, different government organizations and administrations are starting to accommodate CE in their narrative. However, there are only a few counties and cities that are making a slow transition in implementing circular policies and practices. San Antonio, Milwaukee, Palo Alto, and Portland are among the few cities that have deconstruction ordinances. "An important role in buildings' circularity is played by "de-construction", which is understood as "construction in reverse", the ability to dismantle buildings part by part while avoiding damage, in anticipation of maintaining the value by reuse in different contexts."[15] The former mayor of Pittsburgh issued a Deconstruction Executive Order in April 2021 to develop a

[13] Cutaia, L., Altamura, P., Ceruti, F., Cellurale, M., Corrado, S., De Marco, E., ... & EEB, D. S. (2022). A two-year stakeholders' consultation on the construction and infrastructure value chains.

[14] "Von der Leyen presents the Green Deal to the European Council." December 2019. European Commission. Accessed November 27, 2022.

[15] Bertino, Gaetano, Johannes Kisser, Julia Zeilinger, Guenter Langergraber, Tatjana Fischer, and Doris Österreicher. 2021. "Fundamentals of Building Deconstruction as a Circular Economy Strategy for the Reuse of Construction Materials." MDPI.

unified City-led deconstruction policy and establish a City-led pilot program utilizing deconstruction methods on City-owned condemned properties.[16] Despite the fact that this executive order introduces a portion of CE in the city, it does not yet mandate all building stakeholders to adhere to it.

Literature across various countries highlights that organizations moderate the effectiveness of policies and the emergence, and transformation of city-scale CE practices (Bathelt and Glückler 2014; Glückler and Lenz 2016)[17]. However, exactly how the interactions between organizations and policies can be described systematically for their impact on city-scale practices (especially in Pittsburgh) still needs to be investigated (Welch 2016)[18]. As policymakers learn from the experiences of other countries, future policy iterations can articulate more specific standards that advance CE across borders. Intergovernmental organizations can play a critical role in addressing these challenges by operating across borders to understand the state of circular practices and identify who holds critical information on the built environment and public works. As a result, moving from high-level goals to actionable strategies necessitates cities better defining the "how" and building a case for circularity based on precedent and evidence. Cities like Pittsburgh must continue to challenge its policy landscape by convening to share knowledge, exchange data, and build a baseline for the establishment of new CE policies and standards.

PROBLEM STATEMENT & RESEARCH QUESTIONS

The City of Pittsburgh was one of the first in the country to implement the Sustainable Development Goals into its city plans and policies after years of leadership on sustainability. A series of analyses on the development of resilient, equitable, and inclusive communities has been published by the city since 2015. Despite the city being a center for sustainability, circular economy goals have not been specifically addressed in the city's current initiatives and policies. The existing goals can, however, provide close connections to circular economy goals. Through this study, we aim to answer the following question:

> Despite Pittsburgh being a center for sustainability, circular economy goals have not been specifically addressed in the city's current initiatives and policies.

What existing policies are moving Pittsburgh's construction industry toward a circular economy model and how might these be expanded?

METHODOLOGY

Our findings are based on literature reviews, case studies, and interviews with industry professionals who are leading smaller-scale circular economy efforts in Pittsburgh.

Literature Review

We started by looking at examples of successful CE initiatives in European countries, which gave us an insight into the EU CE Action Plan. The next step was to look at the CE initiatives in European countries that have been proven beneficial to the goal of CE and draw parallels with Pittsburgh.

[16] "Deconstruction in Pittsburgh | pittsburgh pa.gov." 2021. City of Pittsburgh.

[17] Bathelt, H., and J. Glückler. 2014. "Institutional Change in Economic Geography." *Progress in Human Geography* 38: 340–363. https://doi.org/doi:10.1177/0309132513507823.

[18] Welch, D. 2016. "Social Practices and Behaviour Change." In *Beyond Behaviour Change*, edited by F. Spotswood, 237–255. Bristol: Bristol University Press, Policy Press.

Case Studies

Case studies are done to recognize the scales of the impact of CE initiatives in countries like Norway, and Denmark. We also looked at cities with deconstruction ordinances in the US. This includes looking at the existing policies and actions taken towards deconstruction in different cities in the US like Milwaukee and Portland, and CE in the City of Pittsburgh.

Interviews

The interviews with industry professionals helped us recognize the lack of CE catalysts and initiatives integrated at a municipality scale that can incentivize stakeholders to design, implement and apply CE principles. We interviewed Construction Junction, one of the largest reuse centers in Pittsburgh and Covestro, a sustainable raw material producer. With the interviews and case studies, we were able to compare our findings and focus on incentivizing existing policies in the material and energy efficiency sector. Material reuse, recycling and energy efficiency play a vital role in motivating CE, and the interviews helped us identify the potential of existing policies and actions.

FINDINGS

CE - Related Policies in EU

Eurocentric approaches to Circular Economy showcase how circularity is conceived and enacted in current policy-making. The countries within the European Union that have adopted national circular economy strategies and action plans are highlighted in Figure 1.

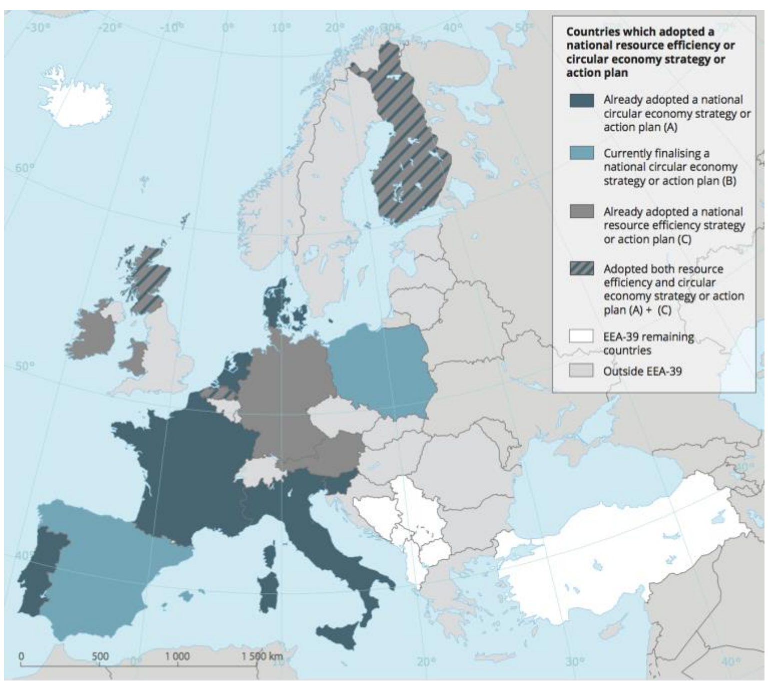

Figure 5.1: Countries that have adopted a national resource efficiency and CE strategy [19]

[19] Developed from European Environment Agency (2019) and EU: https://www.eea.europa.eu/data-and-maps/figures/countries-which-adopted-a-national

EU Circular Economy Action Plan

The European Union's Circular Economy Action plan is one of the pillars of the EU Green Deal that includes measures to stimulate a circular economy, covering the complete life-cycle of products. This plan is a comprehensive body of legislative and non-legislative actions that were adopted in 2015. The European Union established this by rethinking resource efficiency and material flows and developing a framework by engaging policymakers across different policy areas and levels of governance, as well as various stakeholders. By 2019, 54 actions were adopted. Evidently, these policy and regulatory frameworks within the Circular Economy action plan are crucial to the EU construction sector and include the EU Construction and Demolition Waste Protocol and Guidelines & The Construction Products Regulation (CPR)[20], Energy Efficiency Directives, and Level(s).

The EU Construction and Demolition Waste Protocol and Guidelines & The Construction Products Regulation (CPR) lay down harmonized rules for the marketing of construction products in the EU. According to the plan, 21 buildings are responsible for approximately 40% of energy consumption and 36% of CO2 emissions, making it the single largest energy consumer in Europe. Hence, the EU has set a target for all new buildings to be nearly net zero emissions by 2030. To achieve that, following Energy Efficiency Directives (Figure 2) would be important to contribute towards their circular economy goals. The newest initiative, Level(s), is a voluntary reporting framework that assesses the environmental performance of buildings. These are the few common guidelines within the European Union that drive adoption within local contexts as well.

[20] "Construction Products Regulation (CPR)." n.d. Language selection | Internal Market, Industry, Entrepreneurship and SMEs. Accessed December 13, 2022. https://single-market-economy.ec.europa.eu/sectors/construction/construction-products-regulation-cpr_en.

[21] "The EU's Circular Economy Action Plan." n.d. Ellen MacArthur Foundation. Accessed December 13, 2022. https://ellenmacarthurfoundation.org/circular-examples/the-eus-circular-economy-action-plan.

Figure 5.2: EU Regulations for the Construction Sector [22]

EU CEAP Policies, Regulations & Initiatives

Table 5.1 represents a log of policies, regulations, and initiatives established in the specific countries in the EU to understand the various instruments and strategies that contribute towards their circular economy goals.

[22] Developed from Herczeg et al (2014) and EU: https://ec.europa.eu/environment/eusdd

Table 5.1: Scales of Impact: National / Subnational

Country	Policy	Political Instruments
Denmark	The Danish regulation for sustainable construction ("National strategi for bæredygtigt byggeri") 2023	• Requires life cycle assessments for all new buildings from 2023 on. For renovation projects with a floor area smaller than 1000 m^2 , a life cycle analysis is also mandatory. For residential and non-residential buildings with a floor area larger than 1000 m^2, an upper limit for CO_2 emissions per square meter applies. • The regulation foresees that the upper limit of 12 kg CO_2 eq/m^2 /year for emissions during the whole life cycle of buildings with a floor area larger than 1000m^2 will be gradually reduced in the future, once the construction industry has gained more experience with sustainable construction techniques.
France	"RE2020" 2023	• France has enacted a law (RE2020) to reduce emissions from all new buildings, with upper limits related to life-cycle emissions for all new buildings. The carbon ceilings (640 - 740 kg CO_2eq/m^2) depend on the type of building (single-family house, multi-family house) and climate zone, and will be gradually reduced. • The freely available INIES database provides the environmental data on building products needed to perform LCA. Furthermore, a building logbook (Le Carnet d'Information du Logement) will be legally mandatory from January 1, 2023, for new construction and comprehensive energy retrofits of residential buildings.
Netherlands	"The Amsterdam Wood Pact" 2025	• The city of Amsterdam has signed an agreement to build 20% of new residential buildings from wood by 2025. • The Amsterdam Wood Pact brings together material choice (positive impact on emissions) with a focus on circular design, demountable building sub-parts, modularity and prefabrication. To achieve the latter goals, the municipality of Amsterdam is collaborating with 47 other authorities and market participants in the City Deal "Circular and Conceptual Building".
Sweden	"Climate Declaration" (Klimaat Deklaration)[23] 2025	• Project developers will then be required to provide a climate declaration for each new building, including information on the environmental impact of the building throughout its life cycle. • The use of BIM in public tender processes is already mandatory in eight European countries. The use of digital building logbooks, which among other data also store information on emissions, as for example in the case of the Swedish climate declaration shows the manifold opportunities for emission reductions in the construction sector through digitalization.

[23] "A LIFE-CYCLE PERSPECTIVE ON THE BUILDING SECTOR." 2022. Buildings Performance Institute Europe. https://www.bpie.eu/wp-content/uploads/2022/04/BPIE-BE_Good-Practices-in-EU-final.pdf.

Table 5.2: Scales of Impact: Local / Regional

Country	Company / Initiative	Key CE Implementation
Materials and Manufacturing		
Netherlands	Insert	• Developed a marketplace for recyclable materials where companies can buy reusable building materials or offer their own used materials. Also offers a digital material pass, advice for specific material flows, and storage space for recyclable materials. In this way, Insert supports the development of an ecosystem for a circular economy for buildings.
Norway	Loopfront	• Offers an integrated service for building owners to promote circular building. Users can create an inventory of their building themselves. With the help of photos, all parts of a building can be stored in a digital material card and categorized for reuse. Ability to retrieve reports on cost savings, emissions, and waste volumes of construction projects in an automated way.
France	CycleUp	• Offers a service where building elements can be sold on a marketplace. Cycle-up's unique selling point is a comprehensive offer linked to three digital tools: the Digi-it App, the Banski BIM modules, and the Cycle-up library. • The Digi-it App enables the production of a material certificate, but also project planning, and calculation of environmental impacts and emissions based on the National INIES database. • The Banski BIM Module app allows the import of BIM to directly display which materials are available in the marketplace for the appropriate project.
Planning and Design		
Sweden	Basta Logbook	• Gives insight into a building's environmental impact and emissions. It also allows work and information to be shared in different digital 'workspaces' and is directly connected to a database for building product information
Belgium	Woningpas [24]	• Developed for building users and provides a comprehensive digital repository of information on energy efficiency, renovation measures, renewable energy and other data collected by different public authorities. Allows users to share this information with building experts.
Austria	The Circular Concrete (CICO) project	• Shows how a combination of BIM and the reuse of materials can be implemented in practice. BIM and specific digital technologies are designed to ensure the future deconstruction of the building as early as the construction stage. The exposed materials can thus be separated again, processed, and reused for a new construction project.

[24] "Regional programme for a circular economy: Brussels." Ellen MacArthur Foundation. Accessed December 13, 2022. https://ellenmacarthurfoundation.org/circular-examples/regional-programme-for-a-circular-economy-brussels.

After analyzing this information on various policies & initiatives, we identified common CE drivers across the building life cycle phases at different scales of impact (either at a local/ regional or national level). Figure 3 represents a Sankey diagram to trace the common CE drivers and scales of the impact of these policies & initiatives in the EU. Many of these EU Policies advocate for standardizations to be developed for material reuse, material recycling, material passports, and Building Information Modeling (BIM). For instance, developing a regional database to act like a material inventory is a requirement for a few regulations and initiatives like data collection and storage for digital material passports, digital building logbooks, or a digital repository of product information on energy efficiency.

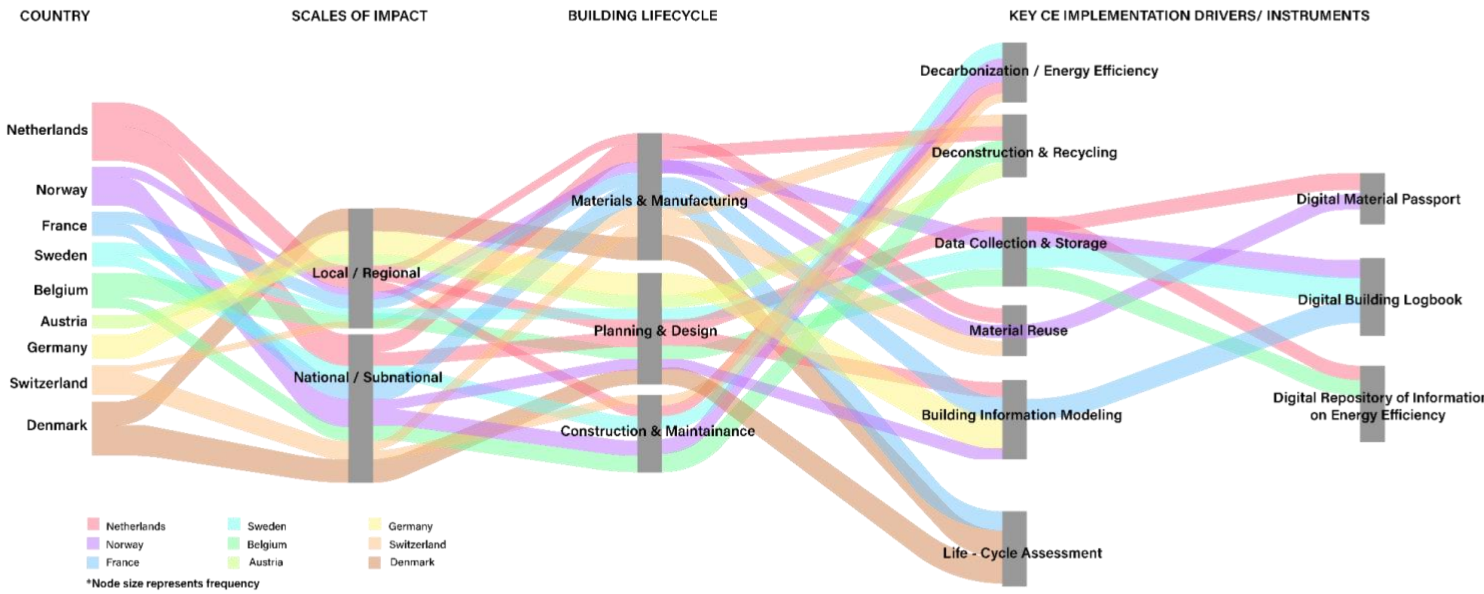

Figure 5.3: Traceability of 'key CE drivers' and 'scales of impact' among EU Policies and Regulations in the Building Construction Industry

For example, Norway has a few regulations and initiatives that contribute towards a circular economy through decarbonization and energy efficiency strategies or digital material passports across all phases of the building lifecycle that are impactful at local levels as well as at the national level. And, at the national level, Norway is implementing policies to decarbonize construction sites by setting requirements for public building sites to become emission-free, which include fostering the usage of electric construction machinery.

Table 5.3: Norway: Scales of Impact

Scale of Impact	Company / Initiative/ Regulations	Phase	Key CE Implementation
Local/ Regional	BIMsync Arena & Catenda	Planning & Design	1. Connect information, tools, and your team throughout the building life cycle with Bimsync. Add, import, organize, and collaborate on issues. Support all the BCF standards as well as the BCF API, allowing seamless collaboration with other design software. 2. Also offers a **digital material pass**, advice for specific material flows and storage space for recyclable materials.
	Loopfront	Materials and Manufacturing	1. Offers an integrated service for building owners to promote circular buildings. Users can create an inventory of their building themselves. 2. With the help of photos, all parts of a building can be stored in a digital material card and categorized for reuse. Ability to retrieve reports on cost savings, emissions, and waste volumes of construction projects in an automated way.
National/ Subnational	NorBetong and Liebherr GmbH4	Construction & Maintenance	1. Zero-emission construction also requires electrical machines and generators on the construction site, which are powered by renewable energy. Ability to deliver emission-free concrete to the construction site 2. Contractors who order concrete delivered emission-free can specify this in their offer to the client and be rewarded for this, through award criteria or bonus points.
	NS ICS 91 - “Building materials and construction” NS ICS 91.040 NS ICS 91.040.99 NS and NS-EN complete (ex NS-EN ISO)		1. Norway’s local administrations are also implementing policies to decarbonize construction sites. The City Council of Oslo has set requirements for public building sites to become emission-free, which include fostering the usage of electric construction machinery. 2. Other cities like Trondheim, Bergen, and Stavanger have set a shared goal, together with Oslo, to make all construction sites for public buildings fossil free from 2021 onwards (e.g. by using biogas), emission-free from 2025 (e.g. by using electric construction machinery) and to make all other construction activities emission-free from 2030 onwards.

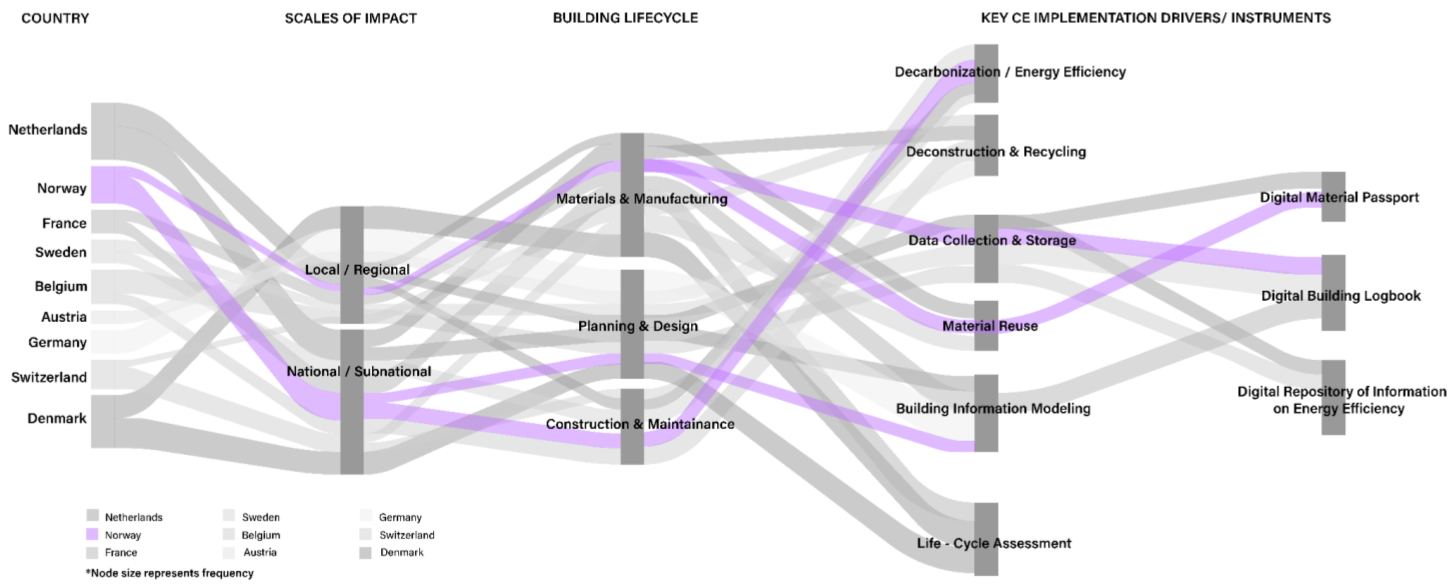

Figure 5.4: Traceability of 'key CE drivers' and 'scales of impact' among EU Policies and Regulations in Norway

Circular Economy in Denmark: A Case Study

A case study of Denmark was explored to identify circular economy opportunities, barriers and policy interventions to overcome these barriers. According to the Ellen Macarthur Foundation, some of the potential Circular Economy opportunities identified in Denmark could lead to a net value of over 200 million euros per annum by 2035. However, the most common barrier faced in implementing these is the unintended consequence of existing regulations. Therefore, some of the policy options that we identified to address this barrier are:

- Augmenting building codes
- Setting a clear legal framework for 3D printing materials
- Creating financial incentives at various scales
- Setting up municipal access portals that provide information on public building availability and matches users with providers

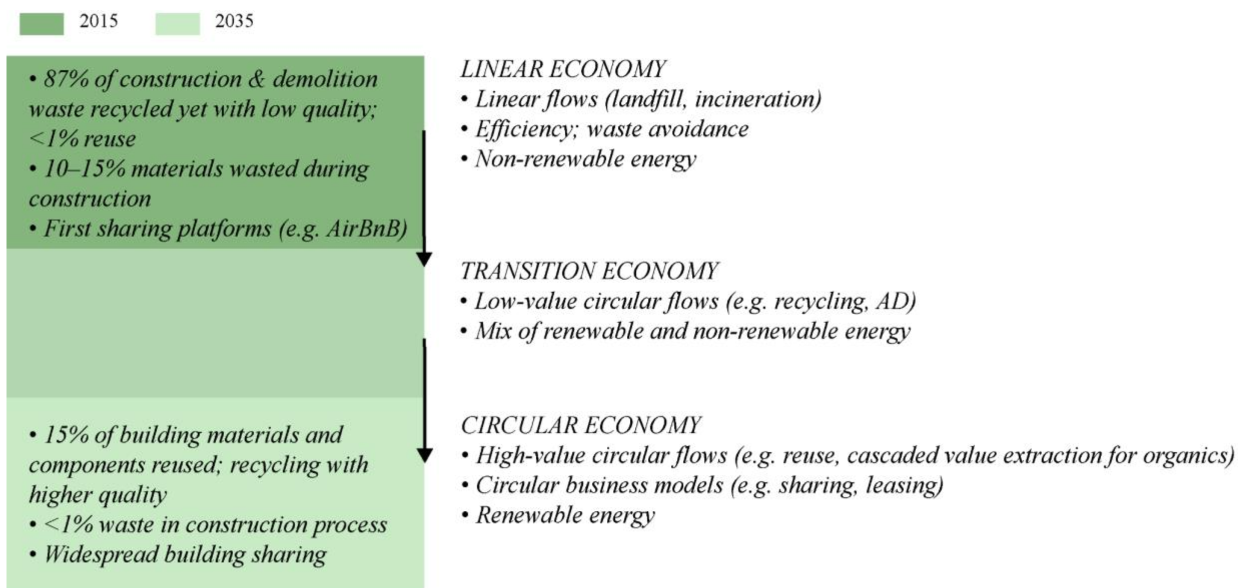

Figure 5.5: Timeline of EU Policies and Regulations Implementation in Denmark

Based on the Circular Economy policy implementation in the EU, a few common factors were identified to guide the transition towards a circular economy in cities in the U.S like Pittsburgh:

- Increasing the ability of assets to respond flexibly to market conditions,
- Leveraging local value chains and suppliers' value chains to co-create innovative solutions tailored to local circumstances.
- Developing a regional database to act like a material inventory.
- Building new partnerships for collaboration to allow for sharing of templates, and knowledge resources across the value chain.

Some of the common EU CE drivers and instruments that can be transferred to Pittsburgh are decarbonization/ energy efficiency, material reuse & deconstruction.

Table 5.4: Identification of policy options in Denmark

CE Opportunities	Key Barriers	Identified Policy Options
Industrialized production and 3D printing of building modules, reducing time and material cost of construction and renovation, could lead to a net value of EUR 450-600 (40-60) million p.a by 2035 (2020).	Inaccurately defined legal frameworks; Immature 3D printing technology; Custom capabilities and skills in the industry	Augmented building codes; Supporting the development of module production facilities; Setting a clear legal framework for 3D printing materials
Reuse and high-value recycling of components and materials, enabled by, e.g., design for disassembly and new business models, could lead to a net value of EUR 100-150 (10-12) million p.a. by 2035 (2020)	Split incentives and lack of information across the construction value chain; Custom and habit; Capabilities and skill;	Complementing building codes with ratings and targets Running industry-wide training programmes Creating support for material inventory software and databanks
Sharing and multi-purposing of buildings to increase the utility of existing floor space could lead to a net value of EUR 300-450 (100-140) millions p.a. by 2035 (2020)	Inadequately defined legal frameworks; Unintended consequence of existing regulation	Clarifying the legislation; Creating financial incentives or financial support to local, regional and national public-sector entities; Setting up municipal access portals that provide information on public building availability and matches users with providers;

Barriers to Deconstruction and Material Reuse

The city of Milwaukee has a deconstruction ordinance that went into effect in 2018. Under this ordinance designated historic structures, and structures in historic districts built in 1929 or before are required to be deconstructed and not demolished. But the city has been having issues with getting bids for those, as a market for the salvage materials has not been established in the city, and there is a lack of trained workers and lack of knowledge. They are also said to have issues finding contractors who are willing to bid for deconstruction.[25] Similarly, The City of Portland adopted a deconstruction ordinance in 2016, which requires all single-dwelling structures built in 1940 or earlier to be deconstructed. They also require structures designated as historic resources to be deconstructed. Portland is the first city in the country to ensure that valuable materials are being reused and that they don't end up in a landfill. [26]Portland has seen many applications for deconstruction come in since the ordinance has been in effect, this is a credit to many reuse materials markets and having

> Milwaukee has been having issues with getting bids for deconstructed homes as a market for the salvage materials has not been established in the city, and there is a lack of trained workers, and a lack of knowledge.

[25]Kilmer, Graham. "The Problems with Deconstruction » Urban Milwaukee." *Urban Milwaukee*, 5 July 2018, https://urbanmilwaukee.com/2018/07/05/the-problems-with-deconstruction/. Accessed 13 December 2022.

[26] https://www.portland.gov/bps/climate-action/decon/deconstruction-requirements

certified deconstruction contractors with the right skills and knowledge.[27] With this success, the deconstruction ordinance in Portland has expanded to houses and duplexes built before or in 1940 also needing to be deconstruction from January 2020. It also requires historic resources to be deconstructed even if they are built after 1940.[28]This has helped in identifying the facilitators for deconstruction, and those are mentioned in the diagram below.

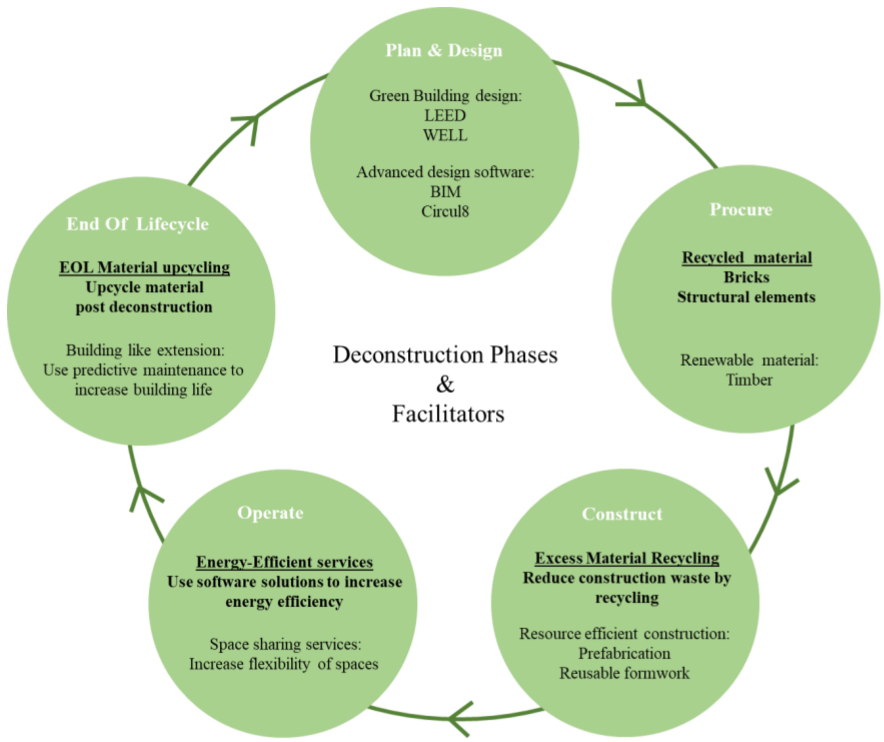

Figure 5.6: Deconstruction Facilitators (highlighted are our focus points)

Once we know the key facilitators, we look at the barriers that we can come across while using these facilitators. Our study of deconstruction in different cities like Milwaukee and Portland has helped us in this, the key barriers are as shown in the diagram below.[29]

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27 Willingham, Emma; Hulseman, Peter; and Paruszkiewicz, Mike, "Deconstruction in Portland: Summary of Activity" (2017). Northwest Economic Research Center Publications and Reports. 32. https://pdxscholar.library.pdx.edu/nerc_pub/32

28 https://www.portland.gov/bds/news/2019/11/19/deconstruction-ordinance-expansion

29 EPiC Series in Built Environment-Using the Circular Economy to Manage Construction Waste

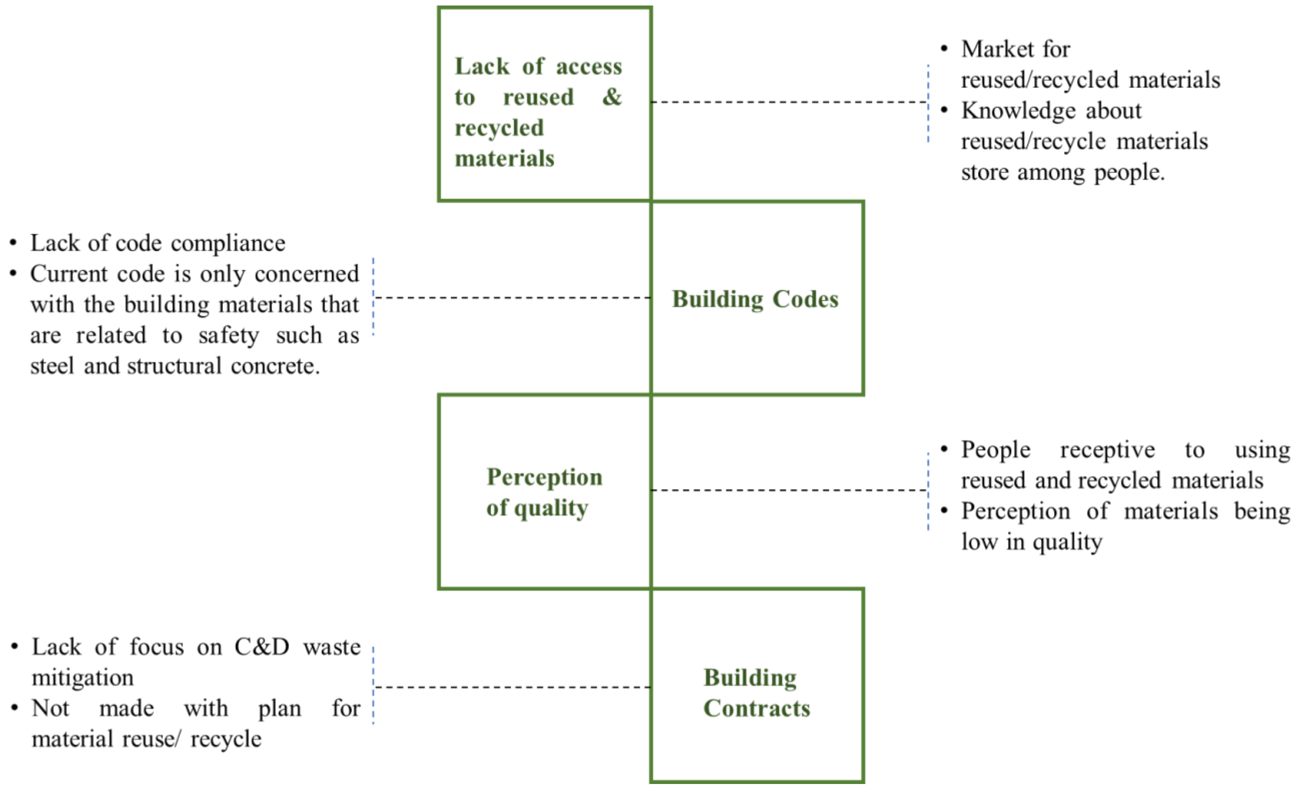

Figure 5.7: Barriers to deconstruction facilitators

Pittsburgh CE Enablers

Analyzing the key circular economy drivers from the study of European policies and regulations; three instruments that facilitate CE implementation and are essential points of commonality between Europe and Pittsburgh are; 1) Decarbonization/ Energy Efficiency, 2) Deconstruction and Recycling, and 3) Material Reuse. Pittsburgh's sustainability goals have captured opportunities within the listed three criteria that can be exercised through a CE lens. The city has goals and initiatives that are being exercised to shift the standard mode of operations and inculcate sustainable practices. In addition to public institutions, private and non-profit organizations are implementing sustainable/CE-centered policies and programs in the city and in their practices. Table 5. lists the initiatives with possible CE leverage points.

Table 5.5: Showing the categorization of policy/initiatives parallel to the CE drivers identified in Europe

Decarbonization/ Energy Efficiency	Deconstruction and Recycling	Material Reuse
NON-PROFIT **Green Building Alliance:** Greater Pittsburgh International Center of Excellence on High-Performance Building is an initiative with goals to advance green construction techniques through stakeholder training and demonstrative projects.[30] The Pittsburgh 2030 district targets aim to achieve zero carbon emissions for new construction and substantial renovations by the year 2030, as well as reduced water use and improved indoor air quality, for existing structures.[31]	**NON-PROFIT** **Construction Junction:** Construction Junction is a non-profit organization that provides deconstruction services in Pittsburgh[32]	**NON-PROFIT** **Construction Junction:** The organization salvages building components that can be reused in the construction of another building **OnePGH:** Resiliency Strategy aims to make the city more resilient by supporting the different sustainability goals including building reuse.[33]
PUBLIC **City of Pittsburgh (Climate Action Plan)** In the Pittsburgh Climate Action Plan 3.0, six important sectors are covered: energy production and distribution, buildings and end-use efficiency, transportation and land use, waste, and resource recovery, food and agriculture, and urban ecosystems. Chapter 3 presents a number of methods for using and sourcing energy for buildings.[34] **Urban Redevelopment Authority:** Under the Pittsburgh Home	**PUBLIC** **City of Pittsburgh, (Deconstruction Executive Order)** The city of Pittsburgh has an executive order which included building assessments, creating pilot programs, incentivizing participation in building trades, deconstruction certification, and city contract and an open policy parameter to use deconstruction to take down privately-owned, dead-end	

30 Algayerova, Olga. 2022. "Pittsburgh International Center of Excellence on High-Performance Building." Green Building Alliance. https://gba.org/initiatives/greater-pittsburgh-international-center-of-excellence-on-high-performance-building/.

31 "Green Building Alliance Initiatives Pittsburgh 2030 District." 2022. Green Building Alliance. https://gba.org/initiatives/pittsburgh-2030-district/.

32 Construction Junction: Home. https://cjreuse.org/.

33 "Pittsburgh's Resilience Strategy One Pgh.pittsburgh pa.gov." 2017. Resilient Cities Network. https://apps.pittsburghpa.gov/redtail/images/8300_OnePGH_Resilience_Strategy.pdf.

34 "City of Pittsburgh." City of Pittsburgh. https://apps.pittsburghpa.gov/redtail/images/7101_Pittsburgh_Climate_Action_Plan_3.0.pdf.

Rehabilitation Program + (PHRP PLUS) the URA provides various grants and technical assistance for Home Rehabilitation. Including Energy Efficiency upgrades.[35]	abandoned homes.[36] **City of Pittsburgh (Climate Action Plan)** The Climate Action Plan also includes goals that promote the recycling of building components and their use.	
PRIVATE **Nexii:** Nexii is a manufacturer of building components. Nexii designs and manufactures innovative high-performance structures and green construction materials that are resilient to natural disasters, economical, and sustainable in the face of climate change. One of their Green New Manufacturing Plants is located in Pittsburgh.[37]	**PRIVATE** **Covestro:** Covestro is leading the polymers industry in Pittsburgh to transition to recyclable products.[38]	

Higher functioning efficiency of the built environment is a central target for these initiatives. However, with higher importance for the policies and initiatives in Pittsburgh on sustainability, the collaborative ways of working with different organizations can help to identify CE implementation opportunities, which have been further discussed in the recommendations section. The public sector is working closely with the non-profits towards the implementation of initiatives outlined by the organizations. Fiscal incentives are not associated with all of the instruments in Figure 6 however, it lays out the methods to answer problems under the three categories. Monetary support or benefits are essential to driving the transition from traditional linear execution methods to circular methods. The city of Pittsburgh and the Pennsylvania Department of Environmental Protection offer financial incentives in the form of initial investment or tax credits through federal and state government programs that can be utilized to make CE-complementing changes.

In Table 5.6 we have summarized different initiatives/policies that can be implemented in Pittsburgh. In addition to municipalities, state governments, and federal agencies, private and non-profit organizations are also represented. To target CE principles through current opportunities, an interconnected approach needs to be taken that has been recommended in the table below.

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[35] "Pittsburgh Home Rehabilitation Program 0% Home Improvement Loan." 2017. City of Pittsburgh. https://apps.pittsburghpa.gov/ura-files/PHRP02072017_db.pdf.

[36] "Deconstruction in Pittsburgh | pittsburghpa.gov." 2021. City of Pittsburgh. https://pittsburghpa.gov/mayor/deconstruction.

[37] "Innovation | Advancing Green Construction Technology." n.d. Nexii Building Solutions. https://www.nexii.com/innovation-nexii/.

[38] "Covestro Solution Center." n.d. Home. https://solutions.covestro.com/en.

Table 5.6: Collaborative methods to implement CE in Pittsburgh

Goal	Method	Circular Strategy	Company/ Technology	Policy/ Incentive
City of Pittsburgh/ Climate Action: 1. Improve energy efficiency in residential, commercial, and industrial buildings 2. Promote Passive House building guidelines ***Urban Redevelopment Authority (URA):*** The Pittsburgh Home Rehabilitation Program (PHRP) offers to help income-eligible City of Pittsburgh homeowners improve their homes	1. Solid wall insulation made of expanded polystyrene (EPS) can be applied to already existing buildings. Applying the rigid foams to the exterior side of walls raises thermal resistance. The insulation reduces the heat gain/loss through the walls and thus minimizes the heating/cooling energy needed. Reduction of CO_2e, PM10, and NOx related due to energy savings. **2.** High-performance coatings for doors and window frames. Polyurethane-based coatings protect doors and window surfaces, as well as enhance their appearance and to extend their lifetimes in a cost-effective manner.	1. Polyurethane foam insulation materials are recyclable and can be returned to the material cycle in line with the circular economy. 2. Using manufactured high-performance windows and doors with disassembly options post one cycle of use. 3. Reusing Doors and Windows and then treating them for high performance.	1. Covestro 2. Nexii-Pella	1. Department of Environmental Protection-Pennsylvania offers the federal government tax credit on the purchase of sealing and insulation products for up to $500[39] 2. Department of Environmental Protection-Pennsylvania offers the federal government tax credit on the purchase of windows, doors, and skylights for up to up to $500 3. URA provides an energy efficiency grant and loan program. Under this program, you may borrow an extra $10,000, and you will receive a $2,500 grant and a longer repayment term of 25 years.

[39] "Energy Efficiency Incentives." n.d. Pennsylvania DEP. https://www.dep.pa.gov/Citizens/Energy/EnergyEfficiencyandConservation/Pages/Incentives-Fact-Sheet-PA-PUC-Electric-Choice.aspx.

Table 5.6 Continued: Collaborative methods to implement CE in Pittsburgh

Allegheny County: Vacant Property Recovery Program The Allegheny County Vacant Property Recovery Program (VPRP) acquires vacant, blighted properties and conveys them to applicants who have developed: A concrete reuse plan and demonstrated the capacity to implement it. Applicants may include individuals, municipalities, community groups, local businesses, and private and nonprofit developers. ***Pennsylvania Department of Community and Economic Development (PA DCED)*** All projects must include a qualified rehabilitation plan that is approved by the Pennsylvania Historical and Museum Commission (PHMC) as being consistent with the standards for the rehabilitation of historic buildings as adopted by the United States Secretary of the Interior. ***Pittsburgh Resiliency Strategy:*** Repurpose underutilized land and building stock in vulnerable places for community benefit	The vacant properties can be reused and not demolished and host different project types against the one that was intended. For example, URA acquired Morningside School for adaptive reuse and utilized the property for affordable housing with 46 residential units.	Adaptive Reuse		The function and organization would dictate the financial incentives. 1. Low Income Housing Tax Credits (LIHTCs) from the Pennsylvania Housing Finance Agency (PHFA) *(used for Morningside school)*[40] 2. New Markets Tax Credit (NMTC) *(used for Mill-19)*[41] 3. Pennsylvania's Historic Preservation Tax Credit (PA HPTC)[42]

[40] PHFA Homepage | Mortgage – Housing – Foreclosure Options. https://www.phfa.org/.

[41] "New Markets Tax Credit Program | Community Development Financial Institutions Fund." n.d. CDFI Fund. https://www.cdfifund.gov/programs-training/programs/new-markets-tax-credit.

[42] "Historic Preservation Tax Credit (HTPC) - PA Dept. of Community & Economic Development." n.d. PA Department of Community & Economic Development. https://dced.pa.gov/programs/historic-preservation-tax-credit-hptc/.

Table 5.6 Continued: Collaborative methods to implement CE in Pittsburgh

Green Building Alliance: Greater Pittsburgh International Center of Excellence on High-Performance Building 1. Focus on best practices for product manufacturing operations with regard to green buildings. 2. Inspire and create demonstration projects to accelerate the adoption of the next generation of buildings and practices.	Train architects, engineers, planners, contractors, and tradespeople in international best practices for sustainable construction, design, and deep energy reduction.	Include circular construction techniques in the curriculum for training.	Green Building Alliance	
Pittsburgh Code of Ordinance Inclusion of LEED Silver Rating as a minimum requirement for commercial buildings.	According to the U.S. Green Building Council, through LEED v4.1 for Building Operations and Maintenance: Existing Buildings, existing buildings have an opportunity to advance the circular economy in their day-to-day operations by making intentional decisions related to purchasing, maintenance, waste diversion and recycling.[43]	The Materials and Resources (MR) credit category in LEED advances a circular economy with credits that reward project teams who minimize and optimize the use of buildings, building products and materials throughout the project lifecycle, from construction and demolition waste management planning to product selection and sustainable purchasing.	LEED Certification	Tax Increment Financing under section 915.06 of Sustainable Development for Publicly Financed Buildings

[43] “The circular economy and LEED | U.S. Green Building Council.” 2022. USGBC. https://www.usgbc.org/articles/circular-economy-and-leed.

DISCUSSION

A circular economy is key to a sustainable built environment in Pittsburgh. As indicated above, there are a few CE instruments that can be implemented with the existing policies and initiatives, but these present only limited opportunities for circularity. The government must establish exclusive CE regulations in order to systematically incorporate its principles not just in the construction sector, but in all organizations.

Previous research has identified policies as a key driver for CE in the construction sector by establishing recycling targets, but little is known about how policies can support the transition in practice. Benchmarking the national CE policy frameworks in EU countries such as Denmark, Finland, Norway, and Sweden revealed that the construction industry was well represented in CE policy documents and that the national policy scene in all countries is somewhat similar in terms of target-setting and objectives. This could be a reflection of EU CE policies for the construction sector, which can be used as an opportunity to be adapted into the Pittsburgh policy framework. Organizations & initiatives reviewed to identify policy links, as well as companies interviewed to identify drivers and barriers, indicated a preference for construction and end-of-life activities in the value chain, as well as waste prevention and recycling activities, indicating their CE focus.

Of the three key policies used by municipalities to facilitate the transition to a CE in the EU and US, i.e., planning, requirements for sustainable construction, and requirements for 2050 Climate Action goals, green public procurement and deconstruction ordinance was mentioned in the interviews as a policy supporting the CE-focused businesses in Pittsburgh. We know that planning and requirements for sustainable construction are elements at an early planning stage, whereas the interviewed companies are active later in the value chain and identified policies supporting their activities or phases of the value chain.

Green public procurement and deconstruction ordinances are the two most helpful policies that would support CE-focused businesses in Pittsburgh.

Limitations

The findings and recommendations are based on literature reviews and case studies. One of our methodologies is also interviewing, our interviews are limited to 2 industry perspectives. A larger sample size would give a stronger idea for the recommendations.

Future Work

This study focused on the key objectives of the policies rather than the enforcement and follow-up mechanisms that ensure implementation in practice. To gain a better understanding of how policies are implemented, the enforcement and follow-up mechanisms could be examined, possibly in light of performance indicators demonstrating the relationship between policy and CE implementation.

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