The Problem of Wasting Useful Life in Modern Buildings

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The Stephenson name I will proudly wear forever and never forget where it came from or what it stands for. This may be the first Master’s Degree for the Stephenson family but will not be the last.

To my father and grandfather, Kevin Stephenson and Martin Stephenson.

Abstract

This thesis investigates the current practice around how buildings are handled when their end of use time comes and the disparity between building life utilization vs building life usefulness in modern buildings. The purpose is 1) to explore the ecological impacts that the current building cycle has on the surrounding environment through greenhouse emissions and define areas which can be improved, 2) to define and explore financial impacts of current building utilization as well as what role finances play in occupants decision making, and 3) to evaluate different ideologies on how buildings useful life can be more sustainably utilized. A secondary purpose of this thesis is to determine and recommend emerging and original design practices, construction practices, and occupancy use plans that can aid in the ongoing effort to make buildings more sustainable.

A building's end of usefulness compared to its end of use exposes the disparity between the two and the faults in current building use practices. As a building's life cycle is generally designed for one function, a major fault in lack of adaptability becomes clear within sustainable construction. Current design and construction practices have limited how long a structure is useful to its occupants by limiting that building's ability to adapt for future uses. When a building gains the ability to adapt through pre-planning on the design end of its life cycle, future functions can be planned for in a way that greatly increases the chances a building can be utilized while still being ecological and economic friendly.

Through the explained framework, a clear path forward on how construction can change buildings that have been historically unsustainable to buildings that can adapt and grow as occupants' needs grow while remaining economically and financially viable.

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List of Abbreviations

CDD: Construction and Demolition Debris
CDDPath: Construction and Demolition Path
CIRIA: Construction Industry Research and Information Association
CO2: Carbon Dioxide
C&D: Construction and Demolition
EOL: End of Life
EPA: Environmental Protection Agency
IRS: Internal Revenue Service
LCA: Life Cycle Assessment
LCCe: Life Cycle Carbon Emissions
MSW: Municipal Solid Waste
ORCR: Office of Resource Conservation and Recovery
U.S.: United States

CHAPTER I: INTRODUCTION

Every year since the United States Environmental Protection Agency [EPA] began collecting structured data on Construction and Demolition Debris in 1990, the total weight of such materials has risen each year. A large portion of these construction and demolition debris [C&D] totals come from the disposal of construction materials that are by definition, in respect to material life cycle expectancy, still useful. Useful life expectancy in referencing materials is the numerical year total that a material under normal circumstances is able to serve its intended purpose. The most recent data (2020) on construction and demolition debris states that of the nearly 600,000,000 tons of C&D debris, twenty five percent was taken straight to a landfill without the materials being used for any sort of second life or recycled uses (U.S. Environmental Protection Agency, 2020). The remaining seventy five percent were labeled “next use” meaning they are intended to serve a future use in a new or similar market. Proper building useful life utilization aims to take advantage of buildings that are not at the end of their designed life cycle. Buildings with useful life are being demolished and at best the demolished materials are being recycled or preserved at a rate of about twenty five percent. The substantial increasing amount of construction and demolition of non-recyclable materials is just one problem from the multifaceted trend that is limiting a building's useful life. It is important to note that there are two definitions of how a structure can be useful to its occupants: The first being a building's structural integrity from the combination of its individual materials that contain the ability to serve their intended or future uses from a structural standpoint. The second form of usefulness is a more general definition of the building's ability to comply with the occupants' desired current or future functions and applications they wish for the building to serve (Wen & Kang, 2001). Taking advantage of a building's full useful life or lifespan offers economic benefits, energy savings, and reduction of carbon footprint (Townsend & Anshassi, 2017).

The problem ideology that has led to a building having aspects of its usefulness wasted (limited) is that occupants and owners design buildings to be functional for much longer durations of time then they end up utilizing. These buildings are designed for specific purposes or functions and when they no longer match the occupants desires, they are being demolished and replaced with new buildings meeting the occupants' new desires. This creates a cycle of utilizing buildings for the amount of time that occupants deem them useful rather than for the amount of times they were designed or are able to be useful. The ability for a building to change and meet the new or shifting demands is referred to as “adaptability”. Adapting a structure or giving it the ability to do so lessens the chance of it becoming obsolete to its current or future occupants. This idea has been addressed from many perspectives, some even stating that buildings are physically designed not to adapt; “Also budgeted and financed not to, constructed not to, administered not to, maintained not to, regulated and taxed not to” (Brand, 1995). With so many limiting factors on buildings' ability to adapt, a disparity arises between a building's usefulness to its occupants and that same building's materials usefulness to serve the physical purpose they were designed to perform. With such restraints on a building's adaptability, a correlation between lack of adaptability and the sustainability of wasting(limiting) buildings' useful life one after the next arises.

Although the concept of sustainable building and material use is becoming more prominent within the construction and environmental fields, there is still a growing problem relating to improper building life utilization practices and the design metrics and methods that are currently used.

CHAPTER II: LITERATURE REVIEW

The Growing Problem of the Useful Life in Modern Buildings Being Wasted: A Literature Review

As an introductory step in this investigation, the present-day literature on modern building practices and useful building life is analyzed. Key topics of literature are organized in three sections: 1) current utilization practices of building and their materials, 2) statistical data on construction and demolition debris, 3) pre-construction design factors, material recycling (environmental), and adaptability. The objective of this literature review is to define and compare the growing problems related to why materials that have remaining useful life are going to landfills and what are the obstacles in achieving any degree of sustainability within buildings' useful life cycles.

Four types of sources were used to examine the literature. These are 1) theoretical, 2) contextual, 3) statistical data, and 4) original research. The theoretical sources are used to examine the origins of building life cycles and the fundamental theory behind how long structures are designed to be used. They can be organized around the two central themes: The concept of adaptability in structures (Slaughter, 2001; Schmidt III, Mohyuddin, & Austin, 2008) and how a buildings usefulness is being determined (O’Connor, 2004; Baker et al., 2017; Liu et al., 2014).The Second type, contextual sources, covers existing research and studies on what happens with buildings after they are built (Brand, 1995; Bullen & Love, 2010; Wen & Kang, 2001). Thirdly, statistical data broken down into the subcategories of: construction and demolition waste (U.S. Environmental

Protection Agency, 2020; Townsend & Anshassi, 2017; Peng et al., 1997), environmental impacts (Jimenez et al., 2018; Pan et al., 2018), and sustainability efforts (Costanza & Patten, 1999; Guthrie & Mallett, 1995; Tang et al., 2020). Finally, original sources that cover a much broader range of ideas relating to building useful life were examined in this thesis.

a. Design Strategies to Increase Building Flexibility by Slaughter

In this article, Sarah Slaughter makes the argument that the ability for a building to adapt has become somewhat of a catch all answer to the question of "How can buildings continue to meet new demands?". As developments in adaptability continue to improve throughout the building industry, a focus towards the pre-construction process becomes more and more prevalent. Designing buildings so they even have the possibility to adapt can be thought of as the first step in sustainable occupancy/owner building use. Identifying a starting point of focus more clearly illustrates how complex of a subject sustainable building life use truly is.

The idea of buildings being adaptable can not be traced back to one point of origin but rather originated as a natural process that some buildings organically experience. The majority of buildings though either can't adapt or occupants choose to not do so. As construction has continued to grow in both volume and individual building size since 1970 (U.S. Environmental Protection Agency, 2020), the demand to limit the growing amount of construction and demolition debris has also risen. This C&D demand has led to the theory of adaptability in buildings, to limit the number of buildings being demolished before their time. In Sarah Slaughter's 2001 article, *Design Strategies to Increase Building Flexibility*, the conceptual plausibility of adaptability being designed into a building during the pre-construction process is explained. The needs of owners and occupants changing over time is explained as a design factor that has been previously left out of the design process (Slaughter, 2001). By anticipating future factors such as occupant wants changing during the design process, buildings can then be constructed with a wider scope, or a scope that can be frequently renovated with minor physical modifications to the building. This anticipation of future wants changing results in significant cost saving when compared to the cost occupancy or user demand. The only physical limiting factor of a building's system is the physical capacity of that building's current in place systems. That leads this thesis investigation to look closer at the association between complete building demolition and rebuild or large scale building renovations (Slaughter, 2001). The difficulty of these changes is determined by the inter-relationships among the buildings' systems. Design strategies that are not only anticipated but factored into a building's expected life cycle can provide specific means to modify these interactions among the systems allowing for not only a smoother transition but also often less expensive. The advantages of these design factors being anticipated parts of a life cycle make the financial decisions behind renovations lean towards sustainable adaptability rather than the unsustainable counter option of demolition. Slaughters research found that these design strategies increase the initial construction cost by less than 2% and usually decrease the original construction duration (Slaughter, 2001). Not only are these design strategies beneficial to the original construction schedule, but a majority of the strategies provide the same benefit throughout the building's complete life cycle, beyond its first renovation. This allows a building to be much more sustainable, as it can adapt to changes in future occupant’s demands for much longer time periods, more comparable to the structure's physical expected life or serviceable time frame.

Author E. Sarah Slaughter is highly regarded in the fields of both civil and environmental engineering through many of her works that include "Assessment of Construction Processes and Innovations Through Simulation, 1997" & "Innovation and Learning During Implementation: A Comparison of User and Manufacturer Innovations, 1992". She has done extensive research on construction engineering and management; building system design and construction; construction innovation; computer-aided process simulation of construction activities; while earning her Ph.D. from The Massachusetts Institute of Technology (MIT) as well as during her consulting stints with The National Center for Manufacturing Science, U.S. Department of Commerce, and Techint Construction Company. In 1995, she was awarded the Career Program Achievement Award by the National Science Foundation. Four years later in 1999, E. Sarah Slaughterbeing was being named the development chair for her alma mater at MIT. The concepts behind the adaptability of structures that Slaughter has formed, during her extensive career in academia, are important to the overall research of useful life in buildings going to waste because definitions of adaptability very similar to hers have garnered the position as the universal starting point to building useful life sustainability. Adaptability, as explained in Slaughter's article, can extend any structure's useful life by addressing the three framework for changes all buildings are affected by at the end of their life cycle. The framework for changes in a building are its functions, the capacity of its systems, and the flow of the environment and people within and around the facility (Slaughter, 2001). Identifying the changes any building goes through in a quantifiable manner allows for the pre-construction sectors of construction to address methods to prolong a building's useful life through adaptability by providing answers to the building's change patterns. Without clearly stated and defined changes in a building' adaptability it would not be considered in a building's design phase. If not considered it would simply fall short of any sort of tangible adaptability that would sustain long term growth and use. Current reasons behind building demolition often solve one of Slaughter's three changes but the two unaddressed changes ultimately lead to the building's useful life going to waste. Slaughters research on building adaptability is so important to the research of this thesis because it displays occupants' affect on adaptability and building changes. Two of the three changes that happen within a building according to Slaughter: its functions and the flow of the environment and people, are changes in the occupants' effect on not only use and demand but also occupant and owners' effect on the adaptability and design processes.

In this article Schmidt III et a.l, investigate how adaptability as a definable design characteristic affects buildings specific systems. Similar to Slaughter's research on designing for adaptability, authors Robert Schmidt III, Syed

Mohyuddin, Simon Austin, and Alistair Gibb researched adaptability through the lens of how the design structure matrix (DSM) could help redefine buildings across multiple sectors. The findings of this DSM adaptability research were originally presented at the 10th International Design Structure Matrix Conference in November of 2008**.** All four authors of “Using DSM to Redefine buildings for adaptability” are renowned for their research in the fields of construction, management, and economics. Their career achievements in academia and research total over 80 years and combined they hold four masters and two doctoral degrees.

The theme of users' impact on adaptability is echoed throughout this research as well. Their central argument is that society as a whole is identified as suffering from the inclination to ignore the causes of problems and instead deal with the effects; this disposition to find a ‘remedy’ rather than a prevention bolsters our tendency to resist change (Schmidt III et a.l, 2008). By examining why certain points of a building’s life cycle are focused on while others are left to their own course starts to narrow the focus on where sustainability in construction is currently faulted. Adaptability as a definable design characteristic with a principle consciousness towards time and layers (Schmidt III et a.l, 2008) builds on to the previously examined theory of identifying future changes a building will experience before they occur (Slaughter, 2001). Both theories on adaptability show the extensiveness that the design phase of a building's life cycle has on the future sustainability of that structure. The problem behind universal adaptability measures that can be valuable across different building sectors is addressed concluding that identifying basic interfaces which can span across a variety of systems and functions is the leading idea to widespread adaptability (Schmidt III et a.l, 2008). The design structure matrix looks to design buildings in an open building system manner as not to narrow possible functions but rather leave it available to accommodate any function with minor adaptations. The development of this generic building model looks to identify all potential design permutations between a buildings ‘parts’. (Schmidt III et a.l, 2008). Schmidt and team also claim the initial differences between the systems clearly show the dependency structure is highly dependent on designers’ thinking (Schmidt III et a.l, 2008). This means that designers thinking at the first stages of a building's life cycle, before ground has ever been broken, decides the fate of that building's possibility to adapt. Their research centers around the claims that establishing a baseline system of parts would help form a consistent supply chain within construction that would then not only allow but encourage future buildings to be constructed as an ever-adaptable generic structure. This research presented to the 10th International Design Structure Matrix Conference is valuable to the advancement of adaptability because it not only echoes the importance of designing with future adaptability in mind but also offers a generic building option with criteria defined through their design structure matrix.

b. Defining Buildings’ Usefulness

When questioning the sustainability of any process or item, the amount of damage caused or long-term effects on the environment is often the metric compared against. Although the final metric or cause that is being designed to avoid is known, the part of sustainability that is often unknown is the length of time that a practice must operate for in order to be considered sustainable. Producing one pound of waste a minute is much less sustainable than one pound of the same waste a year. Even though the metric produced did not change, the rate of occurrence did. The leading metric for understanding sustainable construction and building use is “useful life”. Useful life in the parameters of this research is defined as: The maximum amount of time that a structure can be occupied and or serve a use to its owners with normal maintenance and normal rates of degradation assumed. This maximum amount of time is a collection of the individual material’s life expectancy within the structure. By defining a building's useful life with a standard quantifiable index based on benchmarks that apply to all building sectors, sustainability in building use can be improved with sustainability ripple effects to construction, waste creation, and demolition totals.

In this article, Jennifer O’Connor performed a survey on actual service lives of buildings in North American and aggregated her findings into sections of materials and service types. Jennifer O’Connor, President of Athena Sustainable Materials Institute, has devoted her career to developing cutting edge concepts within green building research. She has focused her area of expertise to environmental performance measurement and accountability in hopes to define sustainability practices that are realistically scalable, adoptable, and financially sensible. Her work has been highlighted in multiple GreenBuild Conferences, MIT and California Berkeley Academic Curriculum, and in numerous scientific journals such as Sustainable Architecture and Building Magazine (SAB).

In O'Connors research, S*urvey On Actual Service Lives For North American Buildings*, which was presented at Woodframe Housing Durability and Disaster Issues conference in 2004, she examined building age, building type, structural material and reason for demolition for two hundred and twenty seven buildings. Her findings over these two hundred and twenty-seven buildings relate to the overall research of this thesis by providing data that is then extrapolated into a theory as to why buildings are not being used to their full useful life potential. Her research on why buildings were being demolished found three reasons for demolition: area redevelopment (34%), lack of maintenance (24%), and buildings no longer suitable for intended use (22%). The most common reason, redevelopment, is completely unconnected to the physical components of the building; this is a change to the use of the land, for example, converting an industrial site to housing (O'Connor, 2004). A key finding in this research is the theory that "no meaningful relationship exists between structural material and average service life [useful life], and that most buildings are demolished for reasons that have nothing to do with the physical state of the structural systems" (O'Connor, 2004).

> *"The vast majority of buildings in this sample fell into just three categories of reasons for demolition: area redevelopment (34%), lack of maintenance (24%), and buildings no longer suitable for intended use (22%). The most common reason, redevelopment, is completely unconnected to the physical components*

of the building; this is a change to the use of the land, for example, converting an industrial site to housing.”

-Jennifer O’Connor (2004)

This is a significant claim in respect to previous theories that sustainability based buildings should be made from materials that have a longer useful life or life expectancy and that material selection was a direct factor of how long a building was utilized. Wood buildings were found to last the longest out of any singular material based building even though its expected life in most cases isn't even half that of materials like steel, concrete, and iron (O’Connor, 2004). She hypothesized the high performance of wooden structures in the past to be due to the fact that residential buildings were made of wood at a very high rate and also occupied for historically longer periods of time. This information is pertinent because it frames a perspective to why buildings' useful timeframes are limited as well as provides totals for buildings that are using their useful timeframe to its maximum potential. With known percentages to begin further research on the effects of user decisions like redevelopment can define a building useful in both anticipated actual use as well as useful to the owner. This is a prime starting point to further explore why the usefulness of buildings’ even if they are designed with sustainability in mind, may become unsustainable due to occupant decisions during its life cycle.

Along the same lines of how user / occupants decisions affect the life cycle of structures, authors Hannah Baker, Alice Moncaster, and Abir Al-Tabbaa give insight in there paper *“Decision-making for the Demolition or Adaptation of Buildings”* into who exactly make up the cast of decision makers that contribute to the question of “what will happen to existing buildings?” (Baker et al., 2017). An interesting idea provided by Baker et al. is the theory that since different functions are represented by different people, priorities that may be beneficial to some individual scopes are not beneficial to the overall usefulness of the building. They specifically call out engineers, architects, environmental managers, planners, developers, quantity surveyors and urban designers as key decision makers who will often have different priorities affecting the building's usefulness to different degrees (Baker et al., 2017). A thought that is parallel to O'Connor's ideas on building life not being related only to what structural materials were used is the common reasons for owners to choose to shorten a buildings life. Those reasons are described as doing nothing and waiting for the market to change, selling the building, adapting the building, or demolishing and building something new (Baker et al., 2017). A reason that this article is valid to the research in this thesis is due in part to the reasons for building retention the authors theorized from their case study findings. Their reason for saving a building included “conserving heritage, the importance of buildings to the community, government incentives – such as permitted development – and architectural quality” (Baker et al., 2017). Their theorized reasoning for those buildings demolished echoed similar ideas to O’Conner (2004) in that the reason for a building's demolition was once again not directly correlated to the material it was constructed out of. Other ideas on causes for building demolition offered that have been examined in this literature review are reasons consisting of "architectural [in]significance, the land could be used more effectively and poor building condition, causing the schemes to be uneconomically viable" (Baker et al., 2017). The final theory in this article, published in the Institute of Civil Engineers Proceedings, is that it is expository, in the investigation of building life cycles, and useful life span, how the decisions of what to do with a building should be evaluated. Framing evaluation of this decision in terms of not just personal occupant satisfaction but that of sustainability within a building's life and use (Baker et al., 2017).

In exploring how a building's usefulness is determined, buildings end up with a numerical duration in years to measure their maximum possible utilization timeframe that is determined through theoretical benchmarks of its overall life cycle.

The final article reviewed for the theoretical framework of determining a building's usefulness is *"Factors Influencing the Service Lifespan of Buildings: An Improved Hedonic Model"* by Department Chair of Construction Management / Professor Guiwen Liu, School of Civil Environmental and Chemical Engineering Professor Kex Xu, Department of Public Policy College of Liberal Arts and Social Sciences Professor Xiaoling Zhang, and Environmental and Chemical Engineering Professor Guomin Zhang's. In their journal piece that was published in "The Habitat International" in 2014, the theory and causation of "the urban renewal process" was dissected. The urban renewal process for all purposes of this research is the development, commonly redevelopment, of a metropolitan area that greatly contributes to demolition of structure to make way for more modern buildings. The article centers around the concept that a majority of buildings being demolished now and in the recent past were demolished indiscriminately during what they have named the urban renewal process (Liu et al., 2014). The urban renewal process for all purposes of this research is the redevelopment of an area that is experiencing social and economic changes (Liu et al., 2014). The article examines the average service life of 1,732 demolished buildings located in seven communities to compile data on the average lifespan of structures. The data gathered on these buildings is relevant to this thesis' research, but the theory on urban renewal practices is what makes this journal article so valuable to the body of research on how a building's usefulness is determined. Liu and team found that of the 1,732 demolished buildings observed, the average age of those structures was only thirty-four years, which is considerably shorter than their average designed lifespan of seventy five years. This is relevant to the research on modern buildings' usefulness being wasted because it exposes some of the complications that determine a building's useful life when a majority of buildings are not being used to the age that would classify as old enough to be beneficial in studying. Another interesting theory presented from the data collected by Liu is the influence that location has on a building's chance to achieve an age anywhere near its designed useful lifespan. Location features generally thought of desirable to a building like "near business centers, railway station, riverside and colleges, far away from the highway" (Liu et al.,

2014) were all theorized to be more likely demolished hence wasting a building's useful life.

In summary, the prevalent theory behind adaptability in buildings and determining a building's usefulness emphasizes the importance of occupants and owners to the building. However different numerical values for a building’s usefulness can be calculated, the factor that ends a building’s life an overwhelming majority of the time is not physical characteristics or used duration but the decisions for occupants to move in a different direction. Both O’Conner and Baker express these ideas in their research and go as far as to back it up with data on physical building characteristics at time of demolition. Slaughter, Schmidt III, Mohyuddin, and Austin place similar weight on occupants by identifying why a building would ever need to adapt and determining that a majority of possible adaptations were due in part to occupants or surrounding human environment changes. The theories surrounding the benefits of adaptability also point towards occupants and their desire to either plan for adaptation or refusal to adapt. Refusal to adapt limits the lifespan of a building and oftentimes makes it impossible for a building to reach its maximum potential useful life. With that being said, many pieces of the literature reviewed point to the opportunity to use a buildings entire potential useful life is contingent upon design factors like adaptability and expected life cycles during the preconstruction process. The thought behind adaptability becoming a design factor or at least a factor that is anticipated is that when adaptability is expected and the building is designed to perform in such a way it will have a positive effect on financials, time savings, and environmental benefits. The theories presented lend to the notion that occupants will not consider how to extend a building's designed life span or how to maximize useful life until it becomes profitable and streamlined to the building’s intended function.

c. What Happens to Buildings Post Construction

Once a building is constructed, the possibilities within its life cycle become much more limited. During different time periods throughout history, buildings have formed different types of relationships with its occupants. “Form ever follows function” is a concept that originated with Louis Sullivan in 1896 and is considered to be the founding idea of modernist architecture (Brand, 1995). The idea that the shape of a building or object should primarily relate to its original intended function or purpose narrows the possibilities for future building adaptations. Designing a building during its pre-construction process to serve one specific function allows form to follow function originally but completely limits any future form following. In order to change the course of modern architecture and occupancy norms, an understanding of how they adapted to get to their current point is necessary (Brand, 1995). In Stewart Brand's book, How *Buildings Learn: What Happens After They’re Built*, he quotes Winston Churchill's idea that “we shape our buildings, and afterwards our buildings shape us.” This is a complex statement but nonetheless related to this thesis study of buildings' useful life because the idea of buildings taking the control on shaping occupants is the power struggle that has led occupants to resort to demolition when the form no longer follows a buildings function. Furthermore, this book is valuable in furthering the understanding of how and why concepts like preservation and adaptability have gained popularity or not. One of the ideas that best presents that understanding is that “the building preservation movement arose in rebellion deliberately frustrating creative architects and the free market in order to restore continuity” (Brand, 1995). This shines a light on the idea that architecture is not a field primarily focused on preservation or sustainability but rather on personal design preferences and agendas. It also states that focusing on preservation brought with it a new emphasis on maintenance and respect for humble order of buildings brought investigation of their design wisdom by vernacular building historians (Brand, 1995). By supplying an insight to how buildings were not only thought of in the past but expected to progress throughout their life cycle, Brand makes possible the comparison to modern day building useful life solutions. Without understanding the occupants' expectations of their relationship with buildings of the past, there would be no basis to begin new sustainable building concepts through the eyes of both architects and occupants. In 1995, at the time of publication, Brand was on the forefront of research relating to investigating the future potential functions a building could one day house. He takes the unknown aspect of a structure's possibilities as the driving factor behind his recommendation to design for as much adaptability as possible.

In the article *“The rhetoric of adaptive reuse or reality of demolition: Views from the field”* by Peter Bullen and Peter Love adaptive reuse is compared as an alternative to current demolition practices. Peter Bullen, a world-renowned researcher and pioneer in the field of adaptive reuse, and Peter Love, professor of Infrastructure and Engineering Informatics at Curtin University and social commerce expert, examine what happens to buildings after they are constructed in a more literal sense of the words. Unlike Stewart Brands' claims on the history of occupants' notions towards their buildings, Bullen and Love examine the rhetoric of adaptive reuse or reality of demolition. They define what they consider to be the physical attributes of a building that influence the decision of whether or not adaptive reuse was the appropriate action for a building. Their criteria that make up these considerations are dimensional characteristics (e.g. physical footprint, dimensional flexibility, size of floor plate), aesthetic appeal, and building type (Bullen & Love, 2010). These physical attributes of a building are said to steer the decision towards or away from any sort of building adaptation and are critical to balance out some of the previously mentioned concepts of occupants or owners making decisions on the building life cycle based simply on personal preferences. This grants some framework toward forming a balanced physical attribute and preference based decision making process. A key claim Bullen and Love make is as follows: “When comparing building options, respondents suggested that a balance between economic, environmental and social outcomes needed to be included in an assessment. Inclusion of only economic objectives would inexorably lead to demolition or redevelopment of the building. Similarly, a focus on purely social needs such as the retention of community, heritage and cultural amenity could lead to an uneconomical building” (Bullen & Love, 2010). Their ideas on factoring economic, environmental and social outcomes open the door to the conversation of where sustainability fits within this context.

In the *Journal of Structural Engineerings 127th Volume* article “Minimum Building Life-Cycle Cost Design Criteria. I: Methodology”,authors Y.K. Wen and Y.J. Kang penned an article detailing their views and ideas on building life cycle costs through the context of natural disasters. Although this thesis focuses its research on a building's useful life being wasted and not disasters reducing the useful life of a building, the framework of expected cost throughout a buildings life cycle provided by Wen and Kang is relevant. Wen’s background as a member of the American Society of Civil Engineers (ASCE) and Kang’s career as a professor at University of Illinois at Urbana-Champaign have positioned them firmly in the construction and civil engineering fields to discuss building life cycle costs and variables. Their journal article centers around explaining the reasoning and relationship between expected total life cycle cost and design specifications to any buildings. Life cycle cost is described as the sum of all costs that the building incurs over its lifespan (Wen & Kang, 2001). Some of these include but are not limited to original construction costs, renovation costs, maintenance costs, and change in function costs (Wen & Kang, 2001). The design specification of a building that are called out as areas of focus that can lower total life cycle cost are future additional investments, and annually recurring costs, minus any salvage value. These design specifications are valid in researching a building's useful life, seeing that they give a foundation that, if considered during the pre-construction design process of a building, would allow for a reduced building life cycle cost. As costs associated with a building throughout its lifespan are reduced, a clearer picture of why some buildings are not taking advantage of their useful life become available.

Wen and Kang focus primarily on the effects of single event instances and the design load related to them; however, design loads can be as simple as the level of pedestrian traffic. “For building structures, the maintenance costs, such as heating and cooling, may be a significant item in life-cycle cost consideration” (Wen & Kang, 2001). No matter the magnitude of events on the designed load, preplanning for a building to handle them and react to them in the least costly manner is critical to properly using a buildings life cycle cost (Wen & Kang, 2001). The use of a building’s life cycle cost to track the financial impact of a building on its owner could allow for a building's useful life that is not utilized due to fiscal reasons to be lessened or avoided altogether. By examining Wen and Kang’s life cycle cost concepts relating to large scale events like natural disasters, a smaller scale life cycle cost can be formulated to help buildings that will experience a different type of load such as occupant demands and normal wear and tear.

To summarize the information gained from the three contextual sources on what happens to buildings after they are constructed, the relationship and building function must be identified. From Stewart Brands observation on past generations relationships with constructed buildings that “form ever follows function” a commanding view of how past occupants were expected to interact with their buildings is explained. Additionally, adaptive reuse was explored in

Bullen and Love’s article through the context of determining if a building was fit for any level of adaptive reuse or if it was going to be determined suitable for demolition. The physical characteristics of buildings that qualified for reasonable adaptive reuse were taken into consideration along with the occupants/owners wants and demands. Lastly, building life cycle cost was identified as one method to apply a physical fiscal number onto a building in order to measure its financial impact throughout its useful life. These three sources, in the context of a building’s post-constructed life, claim to explain occupants' past outlook on their relationships with buildings, the components that factor into the decision to explore adaptive reuse, and how to track a building's cost throughout its useful life cycle. All three of these journal pieces further the conversation of the useful lives of buildings being put to waste with other definable metrics rather than occupants' sole desire for change.

d. Statistical Data on Buildings Life Cycle Impacts

As O’Conner (2004) mentioned, the three categories of reasons for demolition were 1) area redevelopment, 2) lack of maintenance, and 3) buildings no longer functionally suitable for intended use. Although the categories identified are useful for a general understanding of building demolition reasons, a much more detailed data source is needed in order to accurately research the problem that is under-utilized life in modern buildings and the byproducts that wasted useful life creates. Statistical data covering construction and demolition waste, environmental impacts, and mitigation/sustainability efforts are going to be examined.

1. Construction and Demolition Waste

The United States Environmental Protection Agency (EPA) provides data they have collected on construction and demolition debris since 1990. This data is categorized by year, volume in tons, and rate of increase to accurately display the increase of construction and demolition debris totals.

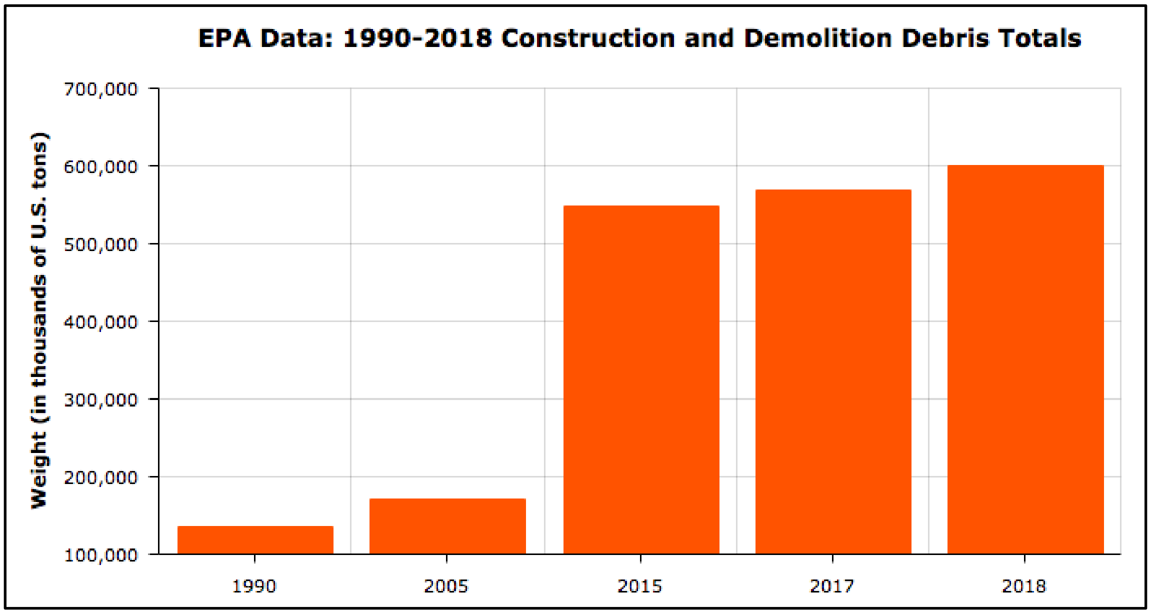

Figure 1: EPA Data from 1990-2018 depicting Construction and Demolition Debris Totals in Thousands of US Tons

Through their research released to the public in March of 2020, multiple estimates of a building's waste from various points along the building's life cycle are compiled. The EPA defines the term “next use” as a destination for materials after demolition that can be used for a new purpose or function. Next use is also referred to as the counterpart to the destination of landfill. “Next use designates an intended next-use market for a C&D material, which depending on the material may include fuel, manufactured products, aggregate, compost and mulch, or soil amendment” (U.S. Environmental Protection Agency, 2020).

The Environmental Protection Agency also collected data on individual building materials waste. They found that concrete, lumber/wood, and asphalt were the three materials that were discarded in landfills at the highest rate in tons.

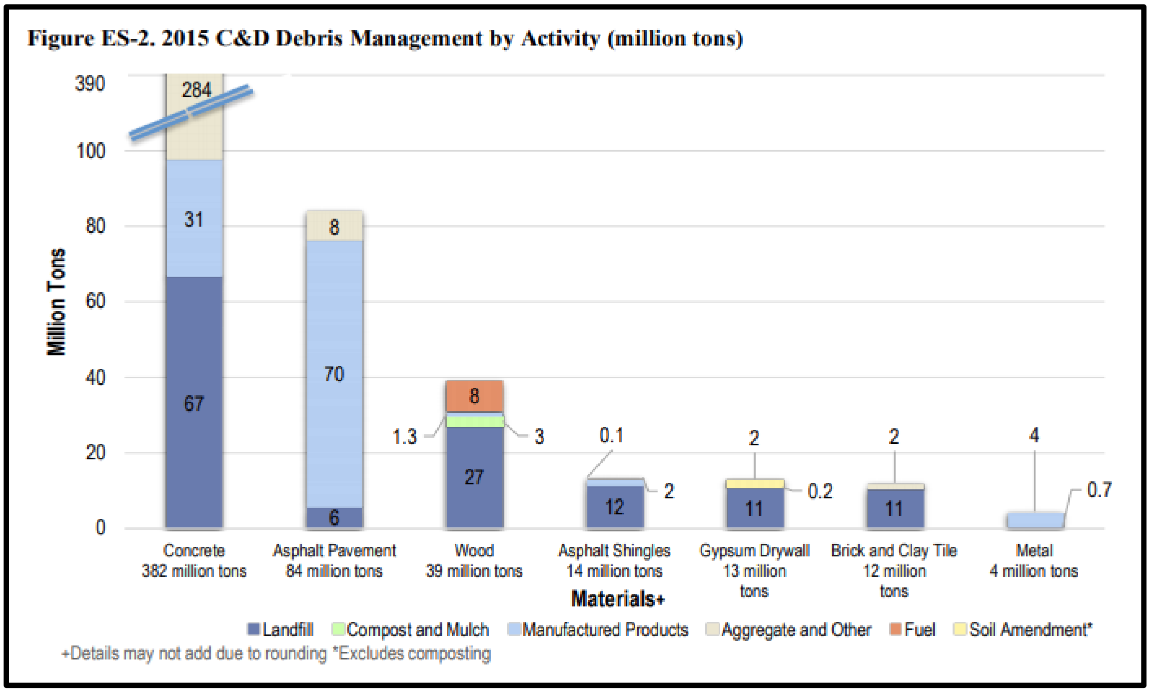
Figure ES-2. 2015 C&D Debris Management by Activity (million tons)

+Details may not add due to rounding *Excludes composting

Figure 2: Construction and Demolition Management by Activity and Material 2015

Those same three materials, concrete, lumber/wood, and asphalt, were also found to have the largest quantity by weight of their final destination being “next use.” Of the next use category, the EPA broke it down into even smaller subcategories that specifically call out the materials used within the broader next use category. The subcategories are described as compost and mulch, manufactured products, aggregates, fuel, and soil amendments.

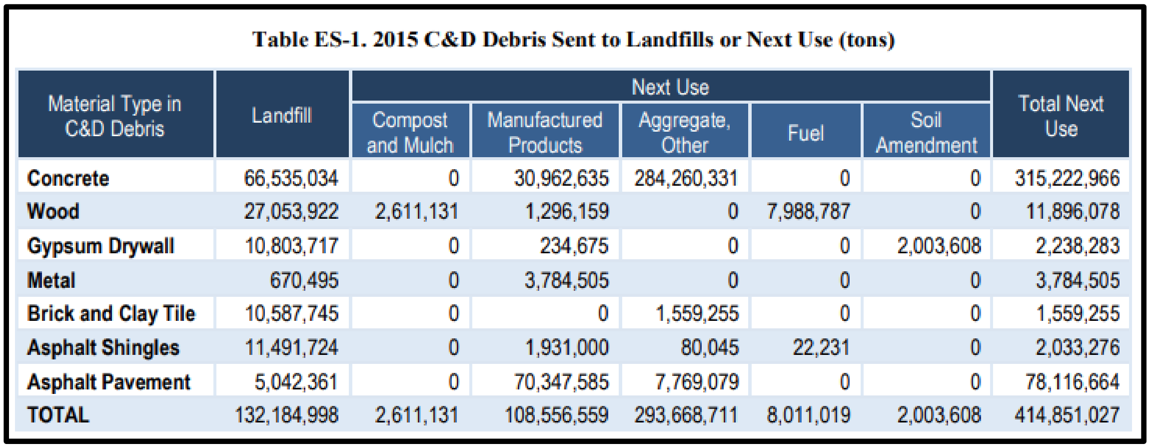

Table ES-1. 2015 C&D Debris Sent to Landfills or Next Use (tons)

Material Type in C&D Debris	Landfill	Next Use					Total Next Use
		Compost and Mulch	Manufactured Products	Aggregate, Other	Fuel	Soil Amendment	
Concrete	66,535,034	0	30,962,635	284,260,331	0	0	315,222,966
Wood	27,053,922	2,611,131	1,296,159	0	7,988,787	0	11,896,078
Gypsum Drywall	10,803,717	0	234,675	0	0	2,003,608	2,238,283
Metal	670,495	0	3,784,505	0	0	0	3,784,505
Brick and Clay Tile	10,587,745	0	0	1,559,255	0	0	1,559,255
Asphalt Shingles	11,491,724	0	1,931,000	80,045	22,231	0	2,033,276
Asphalt Pavement	5,042,361	0	70,347,585	7,769,079	0	0	78,116,664
TOTAL	132,184,998	2,611,131	108,556,559	293,668,711	8,011,019	2,003,608	414,851,027

Figure 3: Amount of Individual Materials Construction & Demolition Debris Sent to Landfill vs Next Use

These statistics from the Environmental Protection Agency are fundamental within the discussion of buildings' useful life for two main reasons. The first reason being, that data this specific and detailed down to individual materials, allows for a better understanding of the wastefulness that improper building life utilization causes on a much broader scale not just single building. The second and more critical reason this EPA data relates to the discussion of buildings' wasted useful life is the magnitude of how wasteful and unsustainable the current demolition debris producing practices are. The rising trend of debris totals that have a final destination of landfills helps to add perspective to how critical and widespread improper use of building life is. The Environmental Protection Agency does offer their form of a solution to increasing construction and demolition waste amounts in the form of a methodology to quantify the end-of-life (EOL) management of the materials (the “CDDPath”) (U.S. Environmental Protection Agency, 2020)”.

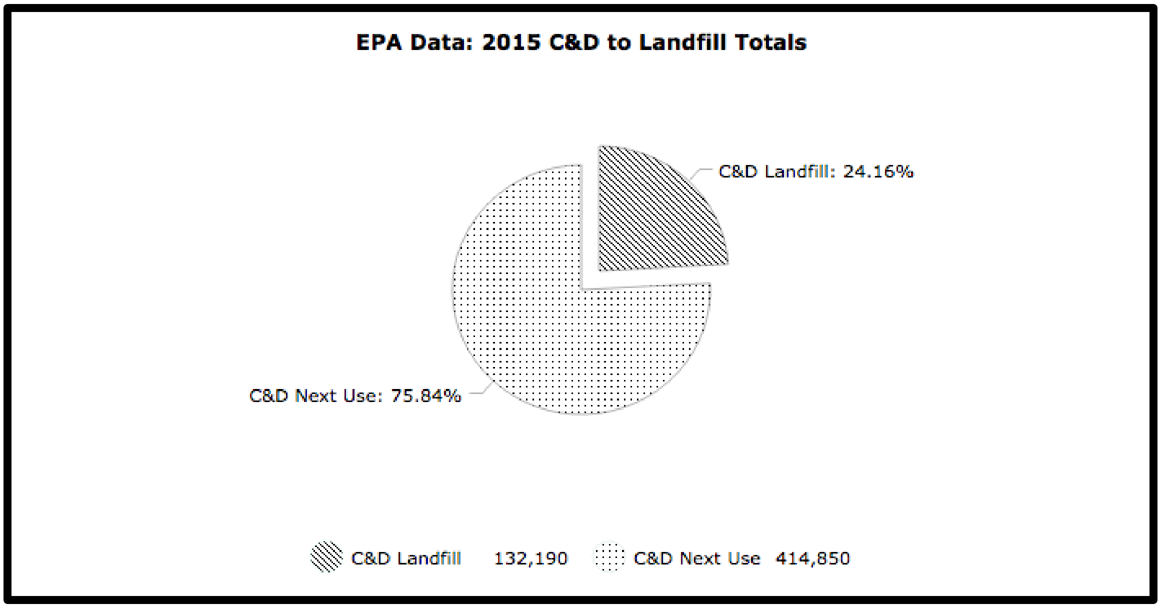

Figure 4: Amount of All Materials Construction & Demolition Debris Sent to Landfill vs Next Use in 2015

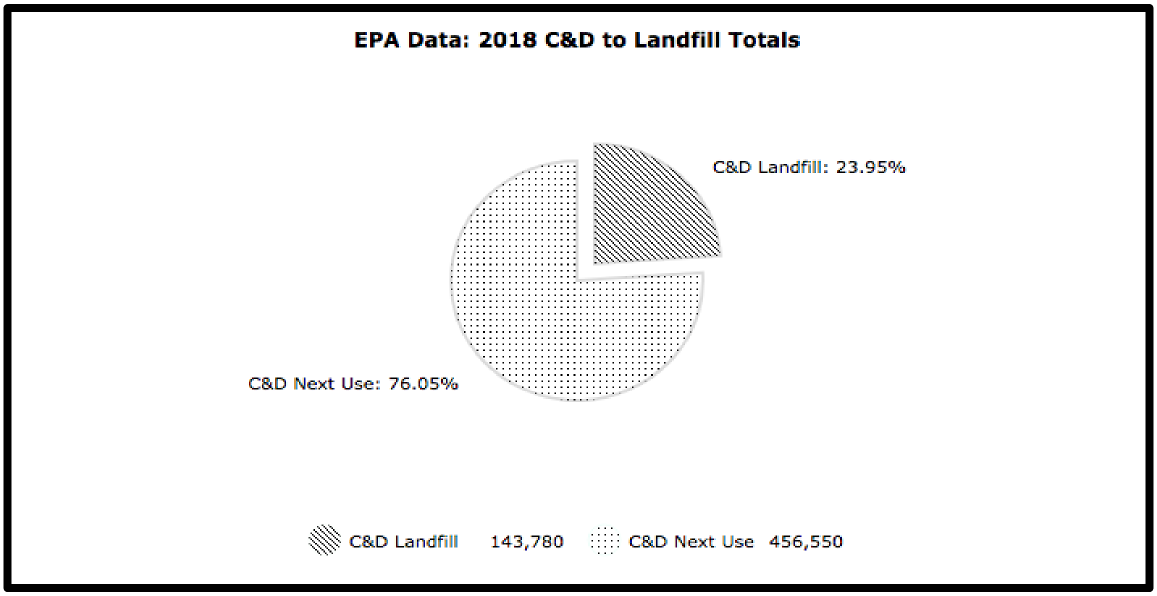

Figure 5: Amount of All Materials Construction & Demolition Debris Sent to Landfill vs Next Use in 2018

Another source examined titled “Benefits of Construction and Demolition Debris Recycling in the United States” by Dr. Timothy G. Townsend dives deeper into the statistical data that makes up the construction and demolition debris obstacle. In Townsend's research for the Construction and Demolition Recycling Association (CDRA), he strives to "quantify the benefits of C&D recycling in the US In order to characterize the benefits of C&D recycling" (Townsend & Anshassi, 2017).

After waste totals were estimated to be as true as possible, construction & demolition recycling industries quantifiable environmental, economic, and social benefits associated with recycling material were listed. In his own words, Townsend stated the difficulty in studying construction and demolition debris was in part due to the fact that "statistics regarding C&D quantities, characteristics, and management in the US have not been tracked in the same detail as municipal solid waste (MSW)." (Townsend & Anshassi, 2017). This is important to any research on building useful life because similar problems in tracking waste totals and environmental impacts at such a large scale across an entire industry make it nearly impossible to have true and accurate data to base claims off of. Townsend also concluded that the benefits of general recycling are now widely recognized by the public, and participation in local recycling programs has become a way of life for most U.S. citizens. However, these efforts that the public are familiar with focus on materials more common in the municipal waste stream such as plastic, glass and metals containers, and paper and cardboard products from printed documents and packaging materials (Townsend & Anshassi, 2017). This familiarity with municipal waste is a positive for the environment, but with concrete alone being such a major environmental point of contention, a shift seems to be necessary in order for construction and demolition debris to be recycled at levels sustainable for widespread use. Construction and demolition materials are used as substitutes for virgin materials in construction projects, raw ingredients for new product manufacture, and fuels for energy production (Townsend & Anshassi, 2017). This is extremely important to note in regards to buildings' useful life as it is a possible solution to the problem that is created when buildings are demolished before their expected maximum life span and create debris that has useful life remaining. Townsend's final three areas he found to have the largest potential improvement based solely on increasing amounts of construction and demolition waste were economic benefits, energy savings, reduced carbon footprint (Townsend & Anshassi, 2017). Energy savings resulted from the avoidance of the raw materials extraction process and transport, as well as the energy gained from combustion of select wastes (Townsend & Anshassi, 2017). "An additional benefit of avoiding the landfilling of C&D materials includes reduced required construction of landfill related infrastructure and associated cost savings" (Townsend & Anshassi, 2017). Although this research is not based on the resulting effects from unsustainable building life use, it inadvertently researches similar effects that stem from buildings being demolished before their maximum life expectancy. Townsend's research gives great insight to the problems that will continue to grow as buildings are improperly used and the widespread effects that it causes relating to economic, energy, and carbon footprints.

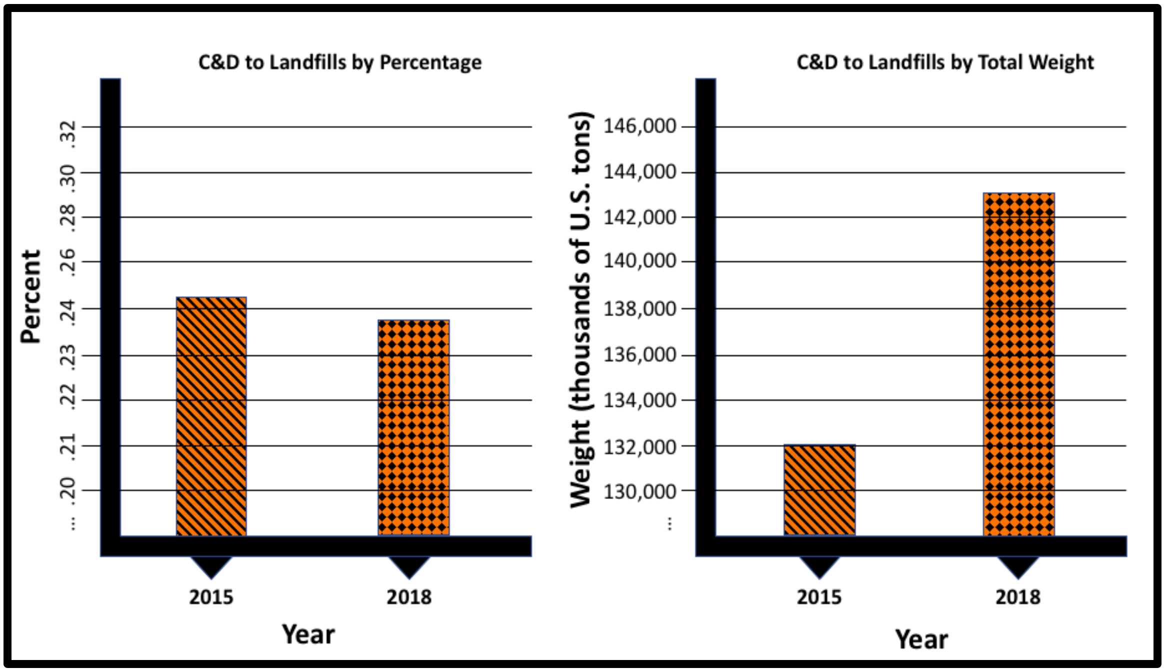

Figure 6: Construction & Demolition Debris Sent to Landfill by Percentage and Weight in 2015 compared 2018

Authors Chun-Li Peng, Domenic E. Scorpio, and Charles J. Kibert wrote an article seeking to answer the question on widespread effects of not utilizing buildings life and its trickle down effect. In their research titled “Strategies for successful construction and demolition waste recycling operations,” the outline for establishing a successful construction and demolition waste recycling operation in the USA today is addressed. With statistical data on total volumes and yearly percent growth on construction and demolition waste as well as identified impacted sectors of industry, the missing piece to achieving sustainability seems to be identifying strategies to solve the problem. Before offering their recommendations and conclusions to the challenges surrounding a successful waste recycling operation, the limiting factors are identified. Peng and associates claim cost from the scarcity of landfill sites and growing concerns from regulatory agencies and the public are the two largest limiting factors to any successful large-scale construction materials recycling operations (Peng et al., 1997). Another factor that is holding back the advancement of sustainable recycling practices include the lack of secondary materials markets, stating that they have not yet matured on any large scale (Peng et al., 1997). Construction and demolition waste is also being denied from municipal solid waste (MSW) landfill operations at an increasing rate (Peng et al., 1997). This is in part due to the sheer size of construction debris taking up massive amounts of space in landfills that are already limited in space. Secondly, municipal solid waste landfills that do have recycling processes are turning away construction-related debris because the government regulations make it more profitable for them to focus on recycling municipal waste materials (Peng et al., 1997). “At present, operators of these facilities make a profit almost solely on tipping fees, with the recycling operation functioning mainly to maintain materials throughout” (Peng et al., 1997). This research and data on how successful recycling operations are set up and why they have not branched heavily into construction and demolition materials is key to understanding the negative bureaucratic impact that is only making unsustainable building use more harmful to the environment. By limiting the amounts of material waste that can be recycled when a building is demolished before its designed lifespan is reached, the amount of waste designated for landfills is increased, thus making improper building usefulness less sustainable and more harmful to the environment.

2. Environmental Impacts from Building Life Utilization

In a 2018 research article for the Chetumal Institute of Technology, authors Luis F. Jimenez, Jose´ A. Domınguez, and Ricardo Enrique Vega-Azamar penned an article detailing their research on assessing the environmental impacts of the production and utilization of concrete. They directed their research on the difference in environmental impacts, concrete production has on the surrounding environment from both recycled and crushed virgin limestone aggregate. This research article relates so strongly to the research on a buildings' useful life because concrete debris from C&D is more than double the next closest debris material total (U.S. Environmental Protection Agency, 2020). It describes not only the harmful impacts of concrete from wasted useful buildings on the environment but also describes the process and benefits of recycled concrete aggregate. "It was also confirmed that cement is the material with the greatest influence on greenhouse gas emissions in the production of concrete" (Jimenez et al., 2018). As concrete was described as an unsustainable material with harmful greenhouse effects, the authors described the benefits of limiting the production of concrete. They also chronicled the importance of using concrete, when necessary, in a sustainable manner that will not end up in landfills in the near future. However, their article makes clear sustainable practices within concrete production are needed. "It was determined that CO2-e emissions decrease slightly by increasing the percentage of recycled coarse aggregates in the concrete mixtures" (Jimenez et al., 2018). This led them to the conclusion that the use of recycled coarse aggregate material has little influence on the reduction of the carbon footprint in the concrete manufacturing process. This is important because they identified the problem concrete production has on the environment via greenhouse gases and noted that improvements to the concrete cycle lie within the amount produced not the amount of recycled materials used. However, their research falls short of defining a course of action outside of proving that their hypothesis that recycled coarse aggregate has little positive effect on environmental factors. However, from their findings on identified points of focus for greenhouse gasses it can be inferred that they recommend the decline in concrete production as the most effective practice in limiting greenhouse gasses effects on the environment.

Although Jimenez (Jimenez et al., 2018) properly identified the problem of building's negative carbon footprints, a true conclusion or course of action was not determined. Authors Wei Pan, Kaijian Li, and Yue Teng dive deeper into why a universal course of action for combating harmful carbon emissions has never been recognized. Their solution to tracking carbon emissions in order to identify what section of the building's life was to be an area of focus is to address a buildings' carbon emissions in a life cycle assessment (LCA) approach (Pan et al., 2018). "Carbon emissions attributed to buildings are a major contributor to global warming.Buildings worldwide consume 40% of energy and contribute 33% of carbon emissions. Apart from operation and maintenance, buildings also demand a large amount of energy and materials for their associated intensive procurement and onsite construction processes" (Pan et al., 2018). Through a life cycle assessment of a building, the stage of life that is most harmful in regards to its carbon footprint can be identified. Even though Pan, Li, and Teng have decided life cycle assessments are the most effective way to track a buildings carbon impact, they cite the inconsistencies in life cycle assessments of buildings in that they often examine different beginning and end points of that building's life. Life cycles in previous studies include studied timeframes: “from cradle to gate, from cradle to site, from cradle to end of construction, from cradle to grave and from cradle to cradle” (Pan et al., 2018).

- The “cradle to gate” system boundary includes the main upstream processes (from the beginning of raw materials extraction to the end of manufacturing and prefabrication).
- The “cradle to site” system boundary covers the “cradle to gate” process, as well as the transportation process of construction product from the factory to the construction site.
- The “cradle to end of construction” boundary further includes the construction and installation process and the waste disposal process. The “cradle to grave” system boundary takes the operations, the maintenance, and refurbishment into consideration.
- With the involvement of the deconstruction and recycling processes, the closed-loop life cycle named “cradle to cradle” can be achieved, which is meaningful for a comprehensive environmental assessment.

As a result of the differing definitions of buildings’ life cycle, the life cycle carbon emissions (LCCe) vary greatly. Original construction and building refurbishment were identified as the two stages within the life cycle assessment that produced the most carbon emissions from processes such as material procurement, material production, material transportation, and material waste creation (Pan et al., 2018). The cradle to cradle timeframe encompasses two separate buildings being constructed. The second building taking the place of the first once it has been demolished. The cradle to cradle also covers any refurbishments that occurred within the first building's life cycle. A widespread life cycle assessment is critical in comparing different buildings' carbon impacts. It is also important to research a building's useful life because the same building could have appeared either more positive or negative when examined through different life cycle scopes.

The framework laid out by Pan, Li, and Teng elaborates on “the boundaries of buildings’ LCCa in the temporal, spatial, functional and methodological dimensions which together contain twelve variables, namely…”

1. life cycle stage
2. lifespan
3. climatic zone,
4. geographic scope,
5. LCA method,
6. research method,
7. unit of analysis,
8. sources of emissions,
9. building typology,
10. level of prefabrication,

11. building material
12. Density

(Pan et al., 2018). The major findings of this paper were that inconsistent timeframe boundaries were found to contribute to LCCa discrepancies, carbon emissions attributed to buildings are a major contributor to global warming, and that reducing buildings' carbon emissions is a matter of urgency and importance (Pan et al., 2018).

3. Sustainability Efforts

In this article *Defining and Predicting Sustainability*, authors Robert Costanza and Bernard Patten, look to form a definition of sustainability that clearly sorts the systems, subsystems, and characteristics that are to be sustained. They also felt it important to define a period of time that those systems in question are to be sustained for. They argue that "because we can only assess sustainability after the fact, it is a prediction problem more than a definition problem" (Costanza & Patten, 1999). Costanza and Patten decided creating a definition of sustainability that can be uniformly applied to differing situations was needed when critics of sustainability began arguing the concept of sustainability was useless due in part to it not being able to be adequately defined. The concept of time being the most important guiding principle to sustainability was identified as being the only metric that was uniform no matter the situation sustainability is being used in. The area of sustainability that applies to buildings useful life falls under Costanza and Pattens ideas of both biological sustainability an "eco-nomical" sustainability. They described biological sustainability as “avoiding extinction and living to survive and or reproduce (Costanza & Patten, 1999)”. When discussing buildings sustainability extinction needs to be replaced with a term that makes more sense in respect to the industry like demolition. Economical sustainability is defined in this article as “avoiding major disruptions and collapses, hedging against instabilities and discontinuities” (Costanza & Patten, 1999). These hedging strategies and instabilities need to be translated into terms that apply to buildings such as switching instabilities as adaptations or renovations. The major take away from Costanzas thesis throughout his article is that “Sustainability, at its base, always concerns temporality, and in particular, longevity (Costanza & Patten, 1999)”. Lastly, this article is useful in the research of buildings' useful life and their life cycle because the idea of sustainability meaning “maintenance forever” is discussed. The authors state clearly that nothing, no matter its degree of sustainability, can last forever and doesn't have to last forever to be sustainable. They state that sustainability needs to be assessed on a localized time scale that it is designed for (Costanza & Patten, 1999). Once a specific predetermined amount of time has passed of the subject's life cycle “sustainability” has been achieved whether buildings or a car's battery life are being examined. The time frame associated with sustainability of buildings has not been specified, rather has been left to future research depending on individual buildings specifics. However, sustainability can still be improved upon based on current status but without a defined time frame “achieving” sustainability is impossible to track. Robert Costanzas research on sustainability is respected as the foremost of his field as he is a distinguished university professor of sustainability at the institute for sustainable solutions, Portland State University. Before moving to PSU in September 2010, he was the Gund Professor of ecological economics and founding director of the Gund Institute for Ecological Economics at the University of Vermont. Costanza's counterpart Bernard C. Patten compliments his knowledge of sustainability with a deep past in ecological modeling and organism-environment relationships. Patten is currently a professor of ecology at the University of Georgia where he is approaching half a century researching and publishing studies on ecology and environmentalism.

The National Academies of Sciences Engineering Medicine published a review titled *"Waste Minimisation and Recycling In Construction - A Review"*. This research and review was sponsored by the Construction Industry Research and Information Association (CIRIA) . They focus their review on producing guidelines on how to improve current existing practices in construction today. They formed three subgroups that construction materials can be classified into based on: 1) potential for reuse in construction, 2)potential for recycling off-site, and 3) lack of potential for reuse or recycling (Guthrie & Mallett, 1995). They formed these three groups and labeled them accordingly in an effort to identify what use is causing said waste and minimize them once identified. Guthrie & Mallett also explain in their thesis that materials change from situation to situation and that no one material can be identified across entire fields to be most effectively prioritized for reuse, recycling, or waste minimisation. This review as a whole is impactful to my building useful life thesis as it not only lays a foundation on how to identify materials that are most impactful to that specific situation but also expresses the dilemma of not being able to identify one material to serve as a catch all material that needs to be recycled or minalized to be most beneficial.

In a journal article titled *Advanced Progress In Recycling Municipal and Construction Solid Wastes for Manufacturing Sustainable Construction Materials,* authors Zhuo Tang, Wengui Li, Vivian W.Y. Tam, and Caihong Xue look to explore the solid waste that is currently being produced in both municipal and construction sectors and what possible positive roles they can serve in lieu of going to landfills. Tang et al. all currently work in the fields of academia and research at either Western Sydney University or University of Technology Sydney in the field of Civil and Environmental Engineering. A majority of their findings center around the possibilities that are associated with geopolymer composites. Aggregates, additives, reinforcement fiber, and fill material were all identified as possible alternative materials that recycled materials could be used in (Tang et al., 2020). Numerous studies examined in this article have been devoted to increasing the recycling rate and reducing landfill rate of construction solid waste. The negative effects of waste materials being incorporated into geopolymer composites were noted especially the depression of some of the geopolymer’s attributes when proper design and portion were not fine tuned (Tang et al., 2020). This article directly contributes to the discussion that arises when buildings are demolished before their designed life span. The ideas mentioned on recycling construction materials in a sustainable manner offer some possible shorthand solutions, to slow down the energy loss caused by construction waste creation. Population growth, booming economy, and rapid urbanization were the three causes that Tang et.al. say have contributed to the acceleration of solid waste generation around the world. A statistic that helps to show the importance of the problem that this thesis aims to offer a solution to is “the annual global generation of solid waste has recently approached 17 billion tons and is supposed to hit 27 billion tons by 2050” (Tang et al., 2020). Lastly, is the past idea, as fact, which is that construction solid waste is a true “inescapable by-product of the construction, renovation, or demolition activities(Tang et al., 2020)”. Dispensing with this idea is going to be a major focal point of this thesis; but also any future advancement in the realm of construction sustainability.

CHAPTER III: BASELINE STATISTICS

When beginning to dive deeper into sustainability within a building's life cycle, having a general understanding of the timeline associated with expected lifespans of both materials and structures as a whole is extremely crucial. The figures given in the following sections were developed off of statistics reported in North American between 1970 and 2020. This time frame is what will be referred to in this thesis as “Modern Day Construction” (U.S. Environmental Protection Agency, 2020).

a. Useful Life Averages

When beginning to examine construction materials, narrowing down which materials to focus on is key. Although technology and construction practices are ever advancing and adapting, a few materials remain constant throughout the industry. The materials chosen to serve as key performance indicators (KPIs) in the context of observed useful life and sustainability were chosen based on their popularity, widespread use and staying power. Popularity was chosen as a material criteria due to its ability to make any findings on said materials applicable to more building types and to more people. Popularity was determined to include both materials that produce the most debris as seen in *Figure 7* below as well as materials that are most commonly used across building types.

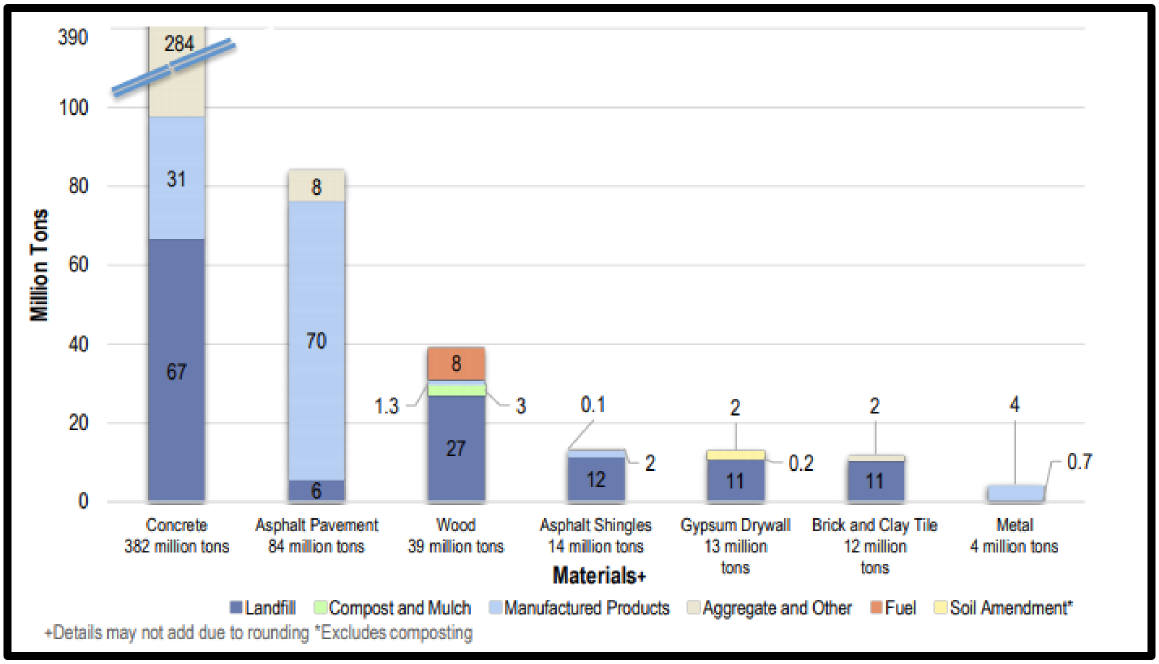

Figure 7: C&D Debris Management by Activity (Million Tons)

Widespread use was identified as a material criteria because a broad range of use can be assumed that a large volume is used making any findings more impactful. Lastly, staying power was chosen as one of the material criteria because observing and researching materials that are going to continue to be used well into the future means any advances to the sustainability of those materials will have a larger impact across a given period of time. In addition, staying power is significant because identifying a material that is extremely sustainable but is not used adds no value to the investigation into sustainability's role in buildings’ useful life. After reviewing construction materials and evaluating them based on the designated KPIs six materials were chosen to be the subject of this research.

These six materials were:

- Concrete
- Brick/ Masonry
- Engineered Lumber
- Glass
- Plastic
- Steel

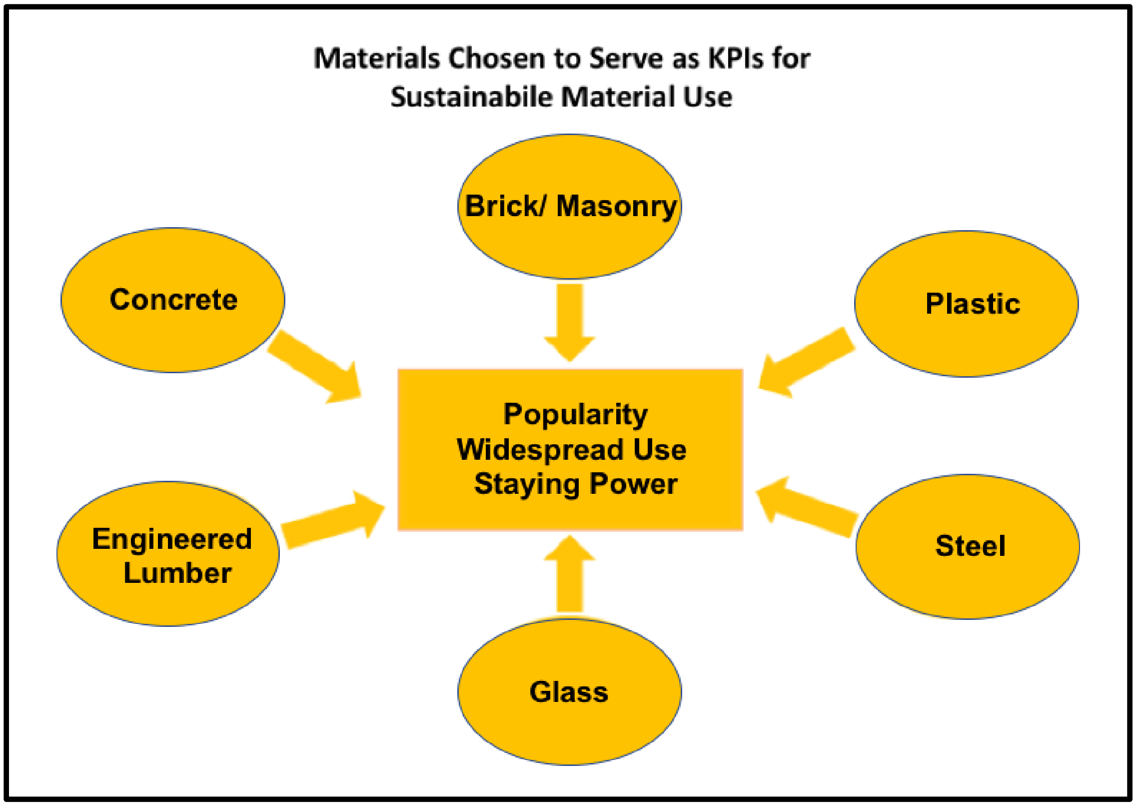

Figure 8: Visualization of Material Selection on the Basis of Popularity, Widespread Use, and Staying Power

In examining the six materials a numerical value correlating to a timespan of a full year of estimated useful life was assigned to each material. For the materials that's useful life was given in the form of a multi year window/range of time, an average of the two numbers was taken (Example: 10-20 years would be averaged to 15 years). This method of determining a single numerical yearly value in order to compare materials is based on Wen & Kangs (2001) methodology that they used while defining total life-cycle cost. Life cycle cost is a useful determining metric for a buildings useful life due to the owner and occupants oftentimes making decisions on the buildings life based on its financial performance and value. In an effort to assign each material a numerical value those materials that are evaluated as having a useful life of “lifetime” a 150 year value will be used in order to maintain a visual representation of years on all graphics. The lifetime value was designated as 150 years in an effort to create digestible data similar to results shown by Townsend & Anshassi (2017) where all of their discovered data is listed based on whole year increments.150 was also chosen as the lifetime data set in order to remain consistent with the understanding that the material will last the designated life it is used.

The following materials' useful life estimated averages all assume normal wear and tear and proper minimum maintenance. Concrete use in all types of construction has a useful life of 150 years (lifetime). Masonry and Brick was found to have a useful life of 100 years. Engineered Lumber has the same useful life as concrete coming in at 150 years (lifetime). Glass and or glazing was found to have a useful life of 17.5 years (15-20). Plastics with a designated construction use have a useful life of 35 years (20 -50). The 6th and final material being examined is steel which has a useful life of 150 years (lifetime) (U.S. Environmental Protection Agency, 2018).

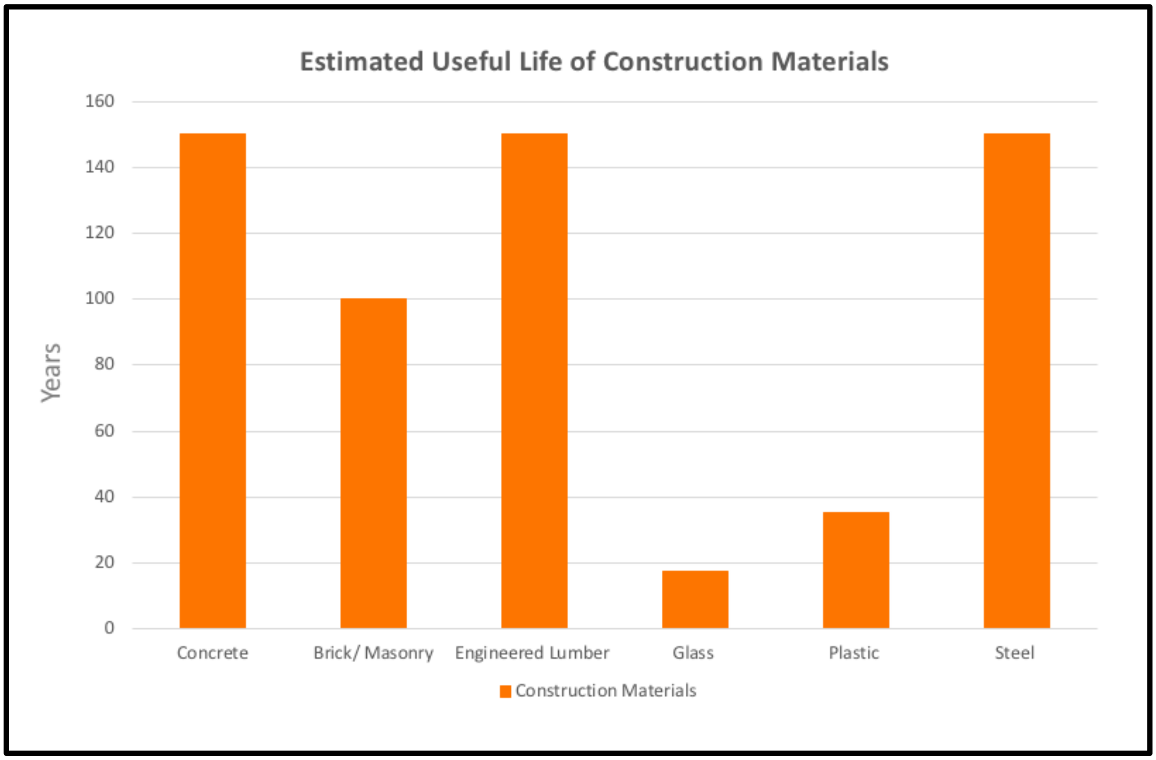

Figure 9: Materials Estimated Useful Life by Material (U.S. Environmental Protection Agency, 2018)

Taking a step back from materials on an individual basis and looking at useful life from an overall building type perspective shows a picture that is more relatable to everyday life. When looking at different building types' and their designed useful life three building types were chosen to collect data on. Those three types were:

- Residential Home
- Commercial Residential
- Commercial Building

These three were chosen based on their popularity from place to place and their applicability to the average person's life. Residential homes observed by the EPA in their Construction and Demolition Debris: Material-Specific Data research, came up with a 200 year average useful life. With nearly half of the useful life of residential homes, both commercial residential and commercial buildings came in with the range 70-100 which was assigned an average of 85 years (U.S. Environmental Protection Agency, 2018).

b. Used Life Averages

With the purpose of this thesis centered around the disparity in useful life and actual used life or utilized life of buildings, the comparison between designed/expected life and utilized life immediately displays the problem. Overall building types used life was determined on a dual defined criteria basis. The two statistics that factored into the dual criteria were demolition statistics from the years 1970-2020 as well as the Internal Revenue Service (IRS) defined depreciation life of a building. The IRS defines useful life in three categories, residential rental buildings, retail commercials, and other commercials. The IRS definition of depreciation is a system based on lowering the value of the item in question based on its lifespan, so that when the item is at the end of its life it has a properly assigned value of zero at that time. This is helpful to the research on design/expect life because the IRS depreciation system properly allows for uniform life expectancy of buildings to be compared no matter the function of the building. The utilized life averages in years for North American structures were as follows:

Residential Home:	85 years (70- 100)
Commercial Residential:	27.5 years
Commercial Building:	39 years

Absolute averages are not quantifiable for individual building types due in part to modern day buildings never being constructed out of a sole material nor built identical to a building with the same purpose. An understanding that utilized building life averages are consistently less than their combined materials have been designed to last is pivotal for the argument of the impactfulness of unsustainable building life utilization.

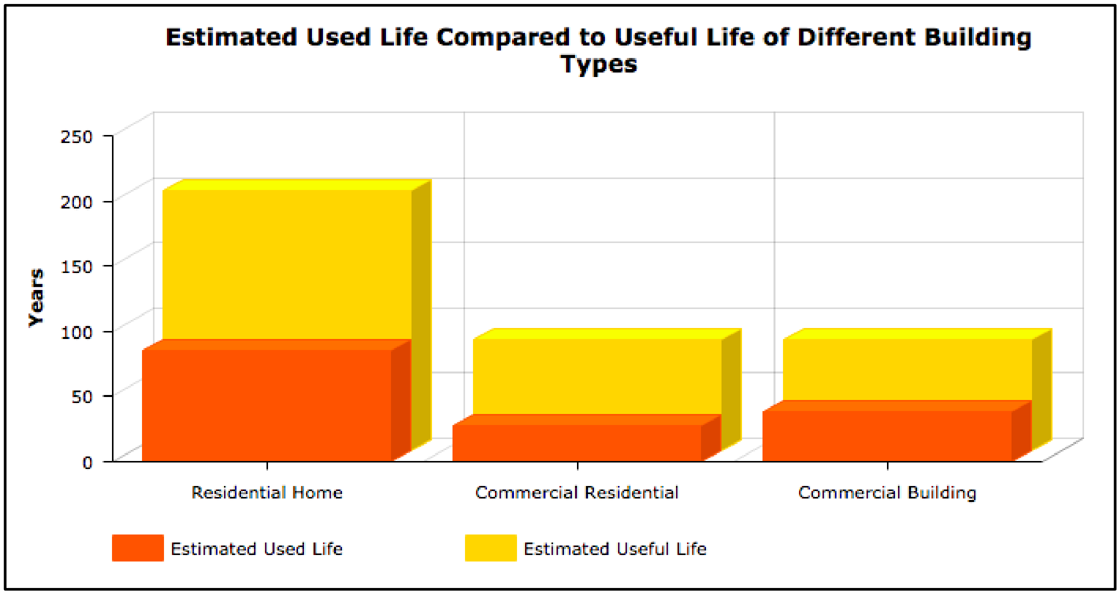

Figure 10: Estimated Life Compared to Used Life for Different Building Types

CHAPTER IV: DISCUSSION

The literature on buildings designed useful life expectancies compared to the literature and statistics on modern buildings current utilization illustrates the growing problem that has become unsustainable building life use. Sustainable building life utilization is a practice that, if implemented on a widespread scale, not only encourages occupants to use the same structure for longer periods of time but also can lower construction and demolition debris totals, lessen the impact of the occupant’s carbon footprint, as well as providing multiple economical benefits. This problem isn't just about saving or reusing old buildings but rather moving the construction industry as a whole towards a more sustainable future. The fundamental issue lies within changing owners, occupants, and architects’ mindsets and plans for a building throughout different stages of its lifecycle and use.

Altogether, there are four main topics that combined are incongruent with the sustainable building life utilization ideology and require this thesis to take a position. They are as follows 1) a realistic and clear definition of what sustainability can be achieved in construction through proper building life utilization and how it can be measured 2) the distinction between necessary and unnecessary construction and demolition debris creation caused by demolishing buildings that could still be repurposed to serve the current functional demands, 3) the clarification on how unsustainable building life utilization is directly contributing to carbon footprints in a negative manner, and 4) the positive economic impact that can be achieved by proper design and use of buildings going forward.

Defined Key Points to Sustainability and Useful Life

First, there is no clear definition throughout any literature reviewed of what a building's “useful life” genuinely is or what sustainability in building life utilization is. “Useful life” of a building is a simple definition that seems for whatever reason to be avoided in discussions of building life cycles. Baker et al. (2017) hints that this could be because an established useful life of a building would expose how poorly buildings are currently being utilized in any life cycle assessments. Useful life of any building has to be defined so sustainability efforts have the necessary time frame to compare against as a starting point. Useful life of a building is: the amount of time during which a building under normal circumstances is expected to be functional and structurally sound.

Costanza & Patten (1999) address the issue around inadequate definitions of sustainability and comparative benchmarks but stop short of providing a definition useful to construction or building life cycles themselves. Sustainability as defined in Webster's dictionary states that it is the “ability to be maintained at a certain level or rate” and also states that it can be defined as the avoidance of the depletion of resources...”. Taking the general definition of sustainability into consideration, sustainability in respects to building life utilization can be defined as the following: The ability of a building/structure to maximize the period of time it is used by its occupants in an effort to reduce the negative effects of demolition, new construction, or renovation in both financial and ecological terms. The depletion of resources that sustainable building life utilization looks to avoid is the production of greenhouse gasses (mainly carbon), debris creation, and energy usage. An easy way to think of resource depletion from unsustainable building life utilization is creating a life cycle for said building that is no more harmful than necessary. This assumes that some portions of a building's life cycle will be harmful to the environment through unavoidable debris creation.

Necessary Debris vs Unnecessary Debris Creation

Second, there is little to no understanding or differentiation between necessary debris creation and unnecessary debris creation or that which could be prevented through sustainable building life utilization. Scholars have different opinions on construction and demolition debris creation generally based on their background and relationship to the point that created the debris. For example Robert Schmidt III et.a.l (2008) come from a background of Civil and Building Engineering and focus their findings/recommendations on factors that tend to be beneficial to their respective fields. They identified the ability to integrate adaptability into the design process rather than it being an afterthought as their ideology to debris creation. In their own words “ignore[ing] the causes of the problems and instead deal[ing] with the effects (Schmidt III et a.l, 2008)” is the problematic ideology currently plaguing sustainability efforts throughout the construction industry. The debris creation they consider to be the problem is demolition debris, that is created when a building does not use any sort of adaptability methods forcing the effects to be dealt with rather than the original problem of designing without adaptability in mind. On the other hand authors such as Jimenez et al. (2018) consider debris handling after it is created to be the solution to achieving some level of sustainability within construction demolition. Jimenez et al. (2018) recommend a plethora of recycling options that vary based on which specific material is in question, but they all center around the goal of lowering CO2 emissions as their definition of sustainability.

When debris creation is examined by either rate or volume it is crucial to understand that in modern day construction in order to have a financially profitable construction project there is an inevitable, even necessary amount of construction and demolition debris associated with any project. This C&D dividend inevitably bookends buildings twice, at their beginning and their end - their construction and deconstruction. Materials such as lumber and rebar are sold in bulk quantities at uniform dimensions that have to be altered in order to build the structure the way it was designed. These alterations or off-cuts, produce materials that are usually not the correct size to be used elsewhere in the project, thus are rarely recycled. This is the necessary (inevitable) debris created during the beginning of the construction process. The necessary demolition debris materials are materials that have reached their designed end of their life expectancy. Materials generated from buildings torn down for structural reasons not reasons having to do with occupants wants or buildings change of function, are again, an inevitability of the end of construction/deconstruction process. Knowing that these two types of necessary debris creation occur during construction and deconstruction, it can then be seen that there are two basic concepts of how to deal with debris creation. Either produce less debris across the board and/or handle it better once it is created.

One solution that addresses both of these debris problems, producing less and handling it better once created, is proper building and material life utilization. The necessary debris creation of a new structure has been addressed but when buildings are not utilized to their full potential two huge negatives arise. The first being the entire building, no matter the useful life the building still has, is demolished and turned into demolition debris. The second being that when a second structure is constructed to take the place of the old building in order to serve the new demands of whoever is occupying that location, the unavoidable debris creation from new construction is produced. This cycle of not utilizing structures for as long as possible, but rather just tearing down and building new to meet new functions or demands creates a negative cycle, where more and more unavoidable points of debris creation between all the new builds and all the demolitions accumulate. One building or structure that has its useful life maximized by its occupants, whether it goes through heavy renovations, or a simple change of functions. Either way, each option produces the only two points of unavoidable or inevitable debris creation in the construction/deconstruction process. When compared to all the points of unavoidable debris creation that unsustainable building life utilization produces, there is considerably less debris in total volume as well as a limited number of unavoidable debris creation points all from just using the original structure to its maximum expected usefulness.

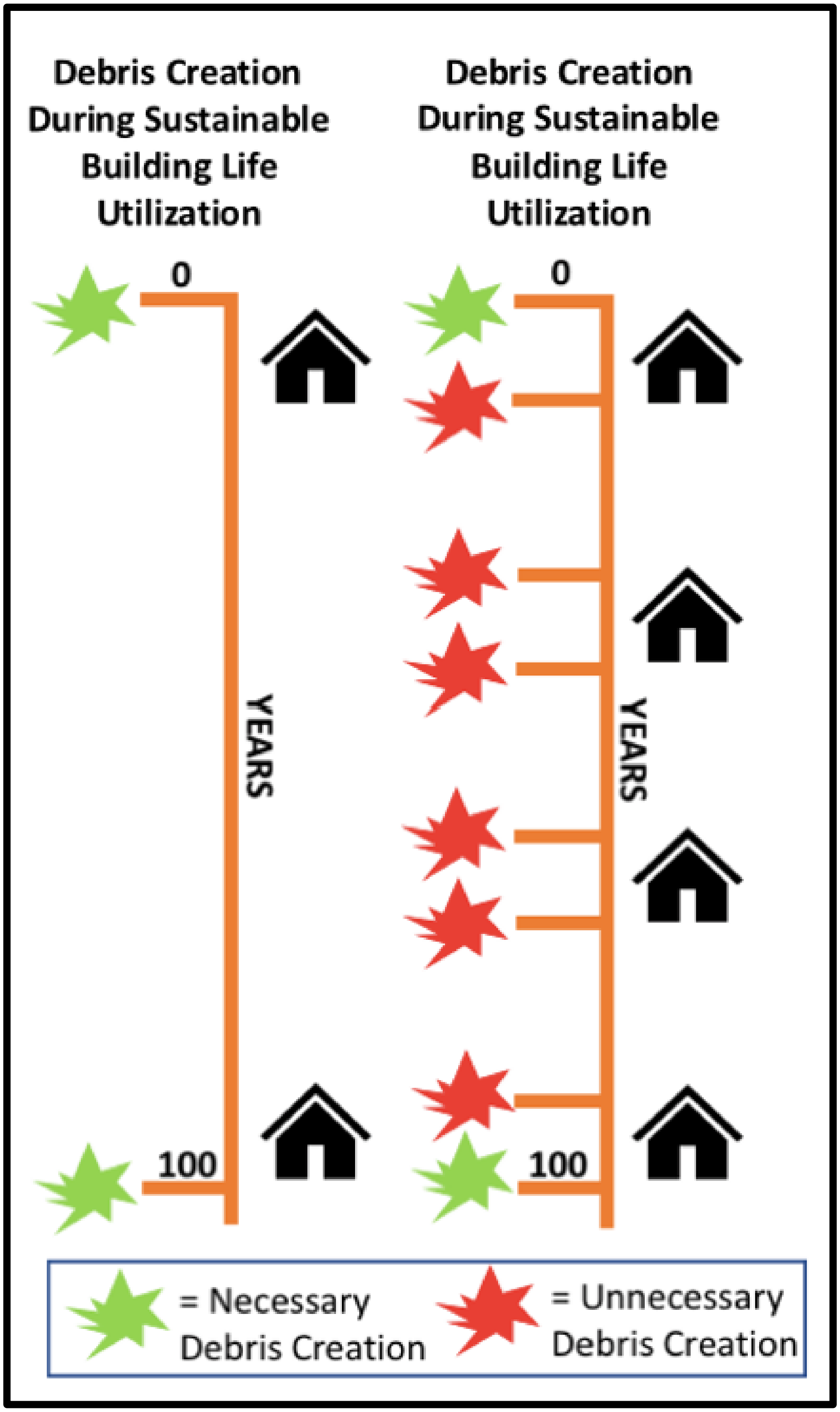

Figure 11: Visualization of Necessary vs Unnecessary Debris Creation During a Buildings Life Cycle

Unsustainable Building Life Utilization Carbon Impacts

Third, as addressed by Townsend & Anshassi (2017), Jimenez et al. (2018), and Pan et al. (2018) in Chapter 3 carbon footprints within the construction industry are being negatively affected from a multitude of different points of carbon creation. Townsend & Anshassi (2017) and Jimenez et al. (2018) both establish their views on carbon footprints being directly related to the amount of recycled materials used in construction projects. Townsend and Anshassi base their carbon calculations on the notion that less carbon is produced by reusing materials compared to the creation of virgin materials. They seem to recommend controlling carbon production by repurposing and renovating materials and or buildings. Jimenez et al. on the other hand, focuses their form of carbon research on only the concrete portion of the construction industry. Concrete aggregates made up of previous concrete that has been crushed and taken the place of virgin aggregates have shown to lower total carbon production compared to concrete mixtures that use all virgin stone aggregates. Pan et al. does not focus on a specific material or even a specific period of time of the building's life. Rather Pan et al. defines the method they consider most useful in tracking carbon emissions is through a life cycle assessment. The life cycle assessment takes into consideration the construction and demolition phases of a building but also factors in occupants' use of buildings and the carbon emission attributed to said use.

The literature review shows that it is reasonable to support both Townsend & Anshassi (2017) and Jimenez et al. (2018) findings as well as Pan et al. (2018)

due to the singular fact that both ideas, lowering volume of concrete produced and reducing debris created, although have different points of focus, all result in the lowering of carbon emissions in some amount. Although the literature reviewed offers solutions to lessening carbon footprints, all the methods reviewed assume the creation of debris can not be changed rather what to do after it is created in order to lower carbon emissions. Only targeting carbon emissions after the point of post debris creation is deficient and wrong because that does nothing to change industry practices to more sustainable methods. Maximizing the use in terms of years of already constructed structures not only can limit the amount of debris created but also could lessen the demand for any other materials, virgin or recycled. It also lowers total energy use, amount of fuel used, and emissions related to transporting materials. Maximizing the amount of time a building is used by its occupants is the solution that can lower carbon emissions at every single step of the construction process. When buildings lives are used unsustainably i.e. not to their full potential carbon emissions are byproducts from every step of that process. Additionally, only a portion of those emissions can be addressed through methods like recycling or reclaiming when all of the emissions can be addressed through the preventative method of sustainable building life utilization. Although impossible based on current unavoidable debris practices and unavoidable emissions in material creation all emissions could theoretically be addressed through perfect and indefinite building life utilization.

Economic Advantage

Lastly, in the literature it is not very clear as to where the economic benefits of sustainable building life utilization originate from. It also is unclear as to which methods or portions of a building's life cycle have the greatest positive economic benefits. It is essential to distinctly identify the financial benefits of sustainable building use in order for wide implementation across the industry. Occupants/Owner decision making, commonly financial based, are the primary driving factor behind building demolitions. The financial benefits of sustainable building life utilization can be broken down into two main areas. The first financial benefit is the cost associated with renovating a building compared to building a new one. As Slaughter (2001) explained, renovating a building to serve a new purpose or function can be conservatively estimated to be roughly thirty percent the cost of building a new structure all together. Not only does this mean that a building could be renovated approx three times before reaching the cost of a single new building but it is also taking into account that buildings will reach their structural end of usefulness before they reach the point of even a second change of function. Slaughter suggests that the average non-residential structure even in the most urbanized city centers will experience less than two total building changes of uses. This is caused by two factors the first being average buildings are demolished before they have time for extended change of functions as well as financial decisions that recommend new builds instead of multiple renovations.

The second economic benefit to sustainable building use is the avoidance of all costs associated with debris creation. Debris creation not only has a cost associated with the process of demolition but also has a price tag associated with the disposal or even recycling of the discarded building materials. Peng et al. (1997) speak to the rationale behind the costliness of debris creation stemming from the unmatured nature of secondary markets available for construction material debris. They also mention the fact that many municipal solid waste (MSW) landfill operations refuse to accept C&D waste at all. In addition to the constant costs associated with the debris discarding process “Tipping fees” have become a silent practice by many landfill operators, agreeing to take construction debris in an effort to make a profit making the discarding process that much more costly.

Financial gains should be examined and tracked through the lens of total life cycle cost. High waste creation time frames occur at the beginning and end of a building's usefulness. So, limiting the number of building life cycle beginnings and ends can reasonably be inferred that it would also limit the financial burden the build/buildings have on their owners. Suggestions on how to achieve this are all throughout this thesis with those that recur the most being renovation when possible and a more in depth design process that will allow for a smoother transition between functions throughout a maximized building life cycle.

CHAPTER V: RECOMMENDATIONS

Sustainable building life utilization requires the consideration of a plethora of concepts and habits during the life cycle of a building. Even though occupants patterns and trends have been observed and estimated there is the need for tangible methods and metrics to be set in place for use when trying to achieve sustainability in building use. While sustainability is becoming an increasingly popular goal across the construction and building industry, the issue has become how to prevent or mitigate the harmful practices that have been identified across the industry on a case by case basis. With this in mind, this thesis has formed three recommendations on how to achieve a more sustainable construction industry through maximizing building life utilization. The construction industry can become more sustainable by minimizing all forms of C&D debris no matter if it is considered inevitable or avoidable. The lessening of any debris is a step in the direction of sustainability. Occupants utilizing buildings that are already constructed for the maximum amount of useful life the structure still has available as well as designing for maximization of useful life in new buildings are both great practices to slow down the trend of unsustainable building use.

These recommendations aim to explore and analyze the main obstacles that currently hinder the sustainability efforts of modern buildings and answer the following questions:

- Is there a uniform process of decision making that can be used across a spectrum of different building types to guide owners/occupants along their decision making process of construction of their building?

- How does sustainability factor into an industry that has long valued economic profitability over environmental impacts.
- How will sustainability be possible in an industry that has necessary waste creation?
- What steps can be taken in the pre-construction process to aid in the future sustainability of the building?
- Are there any gaps remaining in the pursuit of sustainability of constructing buildings that need future explanation?

DECISION TREE

First, a framework for decision making for the construction of a building is necessary in order to achieve sustainability across the industry. The decision making process has been compiled into a decision tree that looks to provide occupants with the most sustainable possible outcome by offering a recommendation based on:

1. Material selection
2. Anticipated building function
3. Anticipated change of functions
4. Urban Development
5. Designed expected useful life
6. Maximizing Financial Profitability

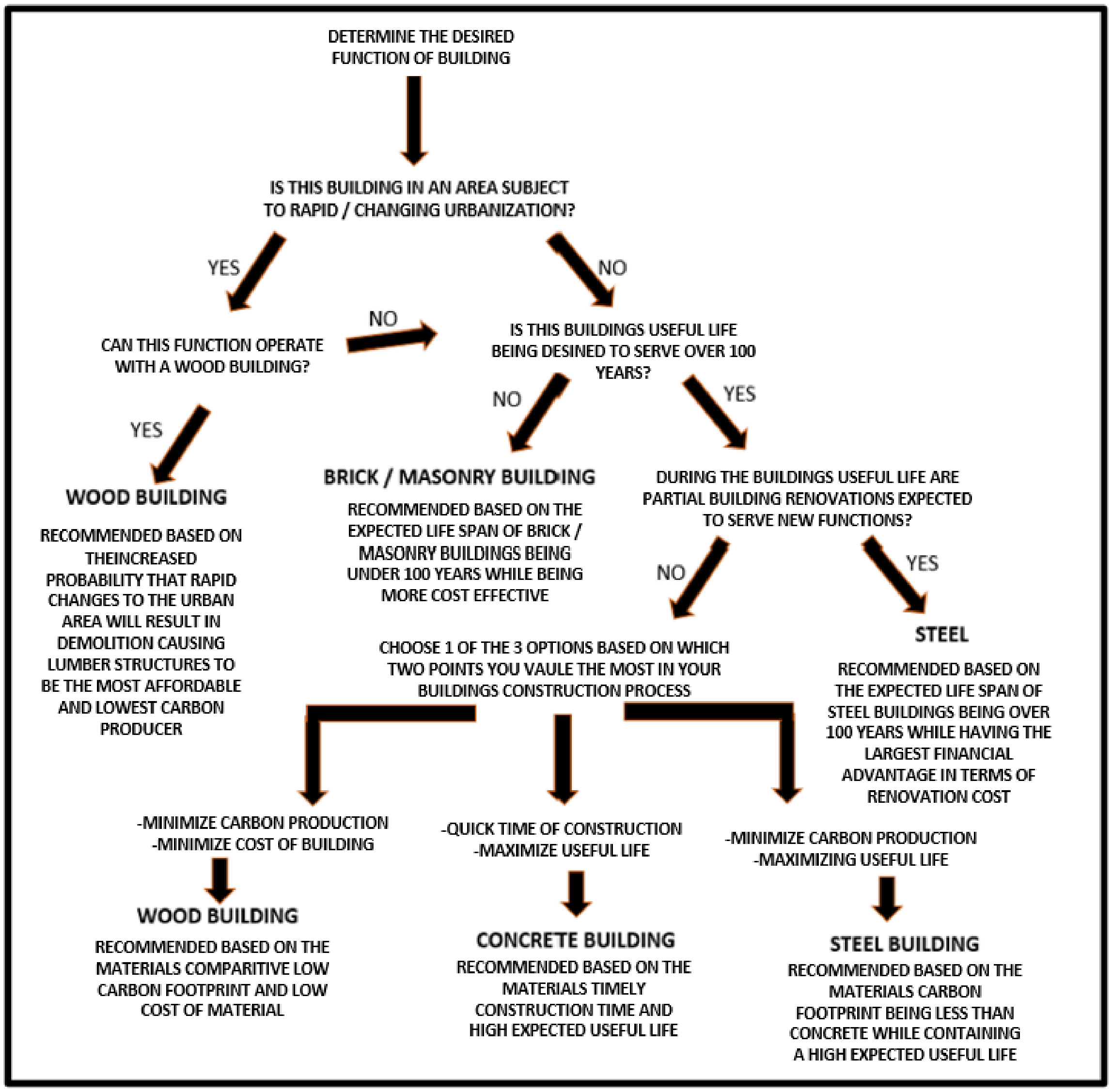

Figure 12: Decision Tree Designed to Recommend a Material That Best Suits a Building's Functional Needs

This decision tree was designed to quickly, easily, and uniformly recommend what material type a building should be made of based on the six factors that were determined to be most impactful to the current lack of sustainable utilization of buildings' useful life. Wood buildings are seen as the material that offers the least amount of carbon emissions, is financially the cheapest raw material, but does have the lowest material useful life. Steel Buildings main advantage and reason of use is its useful life that is higher than any other material all the while having a lower carbon footprint than concrete which is the only other material with a comparable useful life. Brick and masonry buildings are recommended in situations where buildings' useful life falls right in the 60-100 year time span falling just short of steel, seeming like a viable option and requiring a longer useful life and possible adaptability than lumber. Brick and masonry also call for a location that is not expected to pressure the building into a premature demolition situation. A concrete recommendation is the option hardest to reach in the decision tree only being recommended in cases where long useful life building lives are desired, an importance is not placed on carbon emissions, and fast time of construction is desired.

LIMIT DEBRIS CREATON

The second recommendation this paper offers addressed the problems that are created by debris creation. As explained in Chapter IV there are two types of debris creation within the realm of sustainability. Those two debris types are unavoidable, which is the debris created during the buildings original construction and the debris stemming from the demolition of said structure when its useful life has been completely expended, and avoidable, which is any debris created in between the original construction and final demolition of any building on that site. It is recognized that any debris creation is counterproductive to the goal of complete sustainability, the debris that is deemed as the center point of this recommendation is that of limiting the creation of any debris that is not deemed as necessary.

This thesis recommends preventable debris creation by limiting the number of structure builds in a single location to the rate which is determined by the useful life of the original structure placed in that location. If buildings are utilized to their maximized useful life and only demolished when they become structurally unsound at the end of their life cycle the only debris created from any buildings in that location are that of the “unavoidable” category. Modern day utilization of buildings, in the most optimistic estimates, are only utilizing fifty percent of structures' useful life before demolishing them and building a new structure in their place. After reviewing the current literature and data on debris creation the occupant habit or rather pattern of demolishing a building sometimes multiple times before the original structures useful life is up is the main hurdle to achieving a more sustainable debris relationship with buildings.

It is also understood that each building's life cycle has to be examined on a case by case basis and sometimes the function of a building changes faster than the building's useful life is long. In cases where buildings no longer properly serve the desired function in that location this thesis recommends renovations as a less harmful sustainability option. Renovating buildings compared to demolition and new builds is positive both financially and in terms of limiting debris creation. Renovating is roughly thirty percent the cost of a new build and comes without the debris associated to complete demolition or total new builds.

PRE-CONSTRUCTION DESIGN FOR ADAPTATION

The timeframe of pre-construction is such a minimal period of time when compared to a building's total life cycle that it is not being valued across the industry like it truly deserves. This thesis makes the recommendation that a more thorough and detailed pre-construction design process not only increases the chance of occupants utilizing the building longer but also increases the possibility of a more financially profitable building. The last advantage detailed in these recommendations is the importance the preconstruction design process has on a building's ability to adapt to any change of functions.

When future change of functions for a building are not designed for during the pre-construction process there is little to no chance of a building being able to maintain any amount of useful life sustainability or debris creation sustainability. As mentioned in Chapter II, Stewart Brand (1995) specifically states that builds struggle to adapt for the sole purpose that they are designed to not adapt. A pre-construction process that doesnt design for the possibility of adaptation limits the building to a single function it can properly serve. This then leads to demolition and complete new builds the first time a new function becomes desired for that location. Now this thesis acknowledges that a more in depth pre-construction process that addresses design for adaptability and change in function costs more and takes longer to complete. However, the cost and time attributed to a more detailed design stage can be more than justified by the savings owners can acquire through renovating instead of new builds and producing less debris that has to be discarded.

The design pre-construction process that is recommended to aid in the building life utilization and sustainability efforts can be defined in a simple, but generic, four tier design tool. The four tiers in no order of importance are: 1) Design for current function but design broad enough for change of function renovations, 2) Define the expected time frame the current function is anticipated to be, 3) Identify likely next use function that location is likely to demand, and 4) Calculate at what number of change of function renovations is it then more cost effective to demolish and build new.

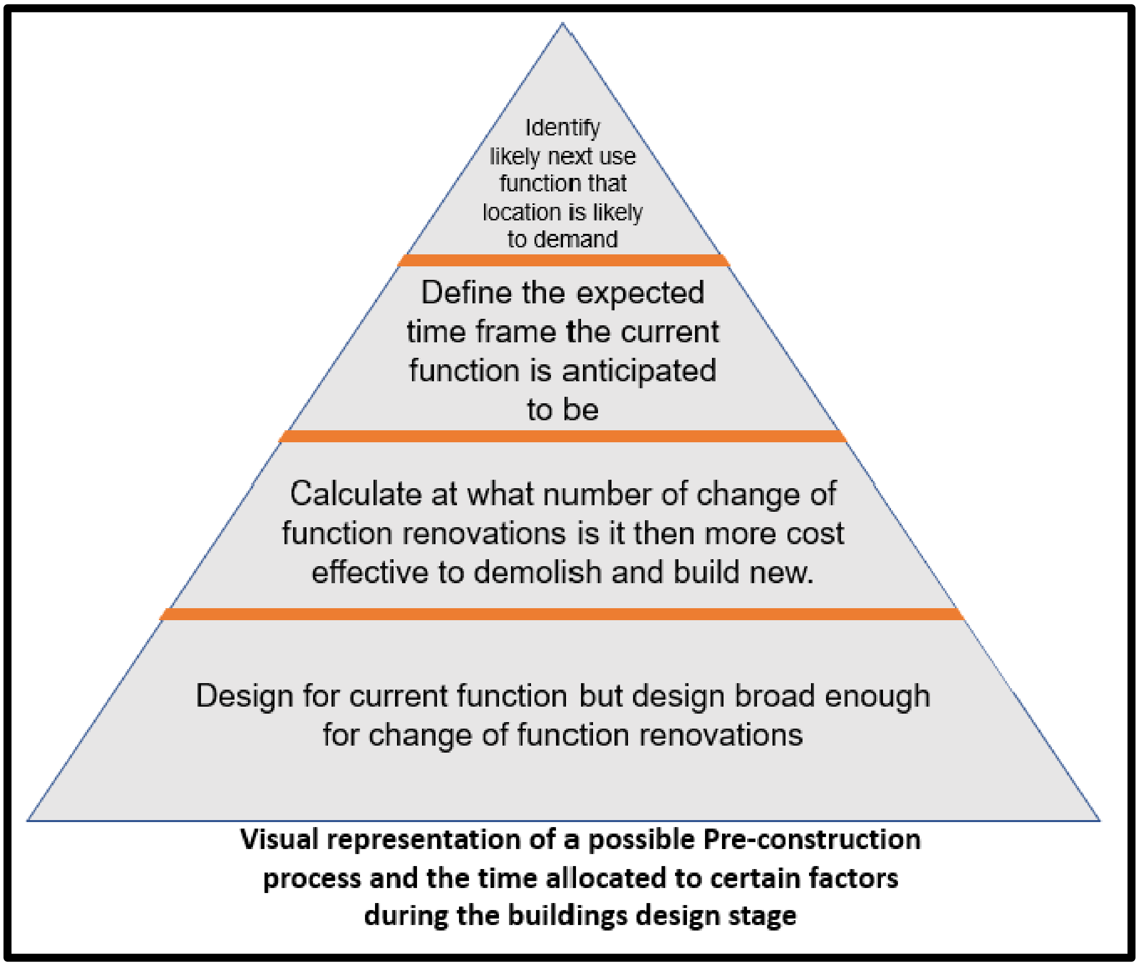

Figure 13: Pyramid Representation of The Preconstruction Process based on time allocation

POLITICAL INFLUENCE

When considering recommendations on how to improve sustainable building and material utilization the recommendation can have a flawless outcome but if it's not adapted within the construction industry by owners and builders it is nothing more than a good idea. In an effort to pressure sustainable choices to be made the third recommendation of this investigation is for governing bodies to impose both additional taxes on non sustainable building related decisions as well as tax breaks on pro sustainable building choices. This recommendation acknowledges the future research and bureaucratic process needed before a true tax plan to aid sustainability can be implemented but considers financial gain or lack thereof to be the most effective way to encourage sustainability throughout the entire construction industry. Some of the possible areas of building occupancy and the construction industry that could be taxed for unsustainable actions are:

- Taxing buildings that are demolished before a predetermined percentage of their expected useful life
- Taxing buildings at a higher rate that directly correlates to a building having a higher embodied carbon total
- Taxing the volume and or percent of C&D created
- Taxing buildings at a higher rate if they do not include designs for future uses or adaptability possibilities for their structure

Some possible incentives for pro-sustainable actions or decision in building utilization or the construction process are:

- Tax breaks for buildings that choose materials with low embodied carbon or other greenhouse gas metrics
- Lowering property tax on structures the longer they are utilized
- Tax breaks for owners who choose to renovate an existing structure rather than a new build
- Incentives for using recycled materials
- Mandating pre-construction plans for expected building life cycle use

Political policy intervention research or financial interventions should be considered as a method of widespread sustainability implementation and tailored by specific location of building as well as building type. When financial implications from policy are introduced owners and builders will be forced to think about their project from a profitability perspective that is not just dependent on cost of materials.

CHAPTER VI: CONCLUSION

This thesis acknowledges the concerns and barriers in route to widespread sustainable building life utilization. It contributes to the current literature by presenting information regarding financial decision making versus the environmental impacts that sustainable building use entails. The importance of this information is an effort to achieve a step in the direction of industry wide sustainable building life utilization. This is deemed important in an effort to reap the positive benefits and avoid or limit any possible negative effects.

Sustainability critics argue that the concept of sustainability is useless because it cannot be "adequately defined" (Costanza & Patten, 1999). However, through a building's effect on factors like debris production, carbon footprint, financial feasibility, and amount of utilization of a buildings maximum expected life sustainability has been shown to be quantifiable. Now the definition of sustainability this thesis uses is centered around the idea of the construction and demolition process to buildings being minimized to the lowest point within reason. Staying within reason is important in all construction related sustainability efforts because in an ideal sustainable minded world construction and demolition would be a zero waste process which is not possible with today's technology. Multiple times throughout the literature review and discussion of this thesis a “necessary” or “unavoidable” amount of actions were identified that go against the general goal of sustainability. However total sustainability within construction is not yet at the technical level where it is financially desirable to all owners despite building type and location.

The proposed framework on how to increase sustainability within the construction process was identified in this paper as being occupants utilization of building useful life. Since utilization of a buildings designed useful life was chosen to be the point of focus for this sustainability research it is critical to note that no reasonable level of sustainability can be achieved without occupant buyin. Sustainability across the industry comes down to the fact that modern day buildings are at the mercy of their occupants' decisions. A heavier concentration on designing for possible building change of use within the pre-construction process of a building allows the occupants the opportunity to choose options for the building that aid sustainable efforts. However, the most sustainable building on the planet is still at the mercy of the decision of its owner or occupants. Sustainability based on maximizing building useful life utilization is not an easy idea to implement into any building. It starts the day a demand for a building is created and ends when there is no longer any demand for a structure on that site. Useful life utilization is defined in this thesis as merely the final step to achieving some form of sustainability based on all the previous decisions that have been made in that build's life cycle. The correct materials have to be chosen first in terms of expected life and carbon footprint. Then, designing for a plethora of possible future functions and finding a way that they could all utilize that same building through as minimal renovations as possible, limiting the debris creation and energy required to bring in new materials. Lastly, occupants have to maintain the upkeep on the building so it stays structurally sound enough to reach the age where maximizing the useful life available is even possible.

A factor that is almost impossible to draw a firm conclusion on due to lack of current research on the subject, but nonetheless important to the discussion of building utilization and sustainability, is that of location of buildings. A trend has emerged that buildings located on land that is of higher value has an increased risk of falling victim to change of functions that result in building demolition to make way for a new structure. As material selection of buildings based on expected change of function and expected used life is taken into account, identifying a buildings site location and taking into account common trends of buildings with comparable locations is a necessary step in designing buildings for sustainable use. More research is needed for definite recommendations on sites impact on building sustainability but if a true correlation between land value and utilized building life is identified then as value of land increased buildings should respond by lowering the expected life of buildings by selecting materials that are anticipated to last the corresponding amount of time.

Multiple sections of this thesis require future research in order to improve upon the recommendations provided on how to improve building use sustainability. Similarly to the impact location of buildings has on occupants utilization is that of cultural determinants and their impact on materials useful life. Current data and research in the field precisely provides yearly totals as well as estimated averages to any material or building type in the market currently. Unlike tangible materials, occupants' cultural determinants have an effect on materials useful life utilization that is much more difficult to quantify. Different areas of the country produce different building utilization trends that seem to spread throughout the surrounding environment. More research is needed to compare different cultural groups throughout different areas to determine occupants trends on building and material utilization. This thesis hypothesizes, upon completion of future research, that occupants are directly influenced on how they utilize a building's usefulness based on past trends of buildings in the surrounding environment. The problem, although not yet adequately defined, lies within more than just materials possible maximum useful life. Without addressing cultural detrimental factors of why buildings are currently performing unsustainability in respect to utilization, buildings will continue to be demolished with useful life left in their materials. Identifying cultural determinants could also aid in the pre-construction/design process of material selection. In areas where no matter what designed useful life or material choice is selected are demolished around time frames materials with lower cost and environmental impacts can be used. Any research into cultural determinants will produce outliers but the goal of improving overall industry wide building sustainability can still be improved based on future research geared towards trends between occupants and their buildings based on cultural geographical determinants.

The second portion of this thesis that requires future research is the decision tree this thesis produced as a recommendation in Chapter V. Although a solid foundation to build on, the decision tree requires further research in order to improve it to the point of everyday implementation. The decision tree falls short of specific material type recommendations within the type of material category. More specific material types such as low embodied carbon concrete once concrete is chosen or recycled steel once steel is selected. Taking material recommendations a step further is required in order to optimize positive sustainability impacts, instead of just recommending a general material that is more sustainable than other options. The decision tree also requires more in depth guiding questions in an effort to avoid all buildings being recommended to different lumber types due to their low financial cost and positive environmental impacts.

In conclusion, the need for a more sustainable construction and building use practice is undeniable. All the data reviewed shows a continuously increasing production in harmful greenhouse gasses and debris creation stemming from the act that is unsustainable building life utilization. It is becoming more clear that sustainability of buildings in general can be planned for and designed to achieve but occupant participation in sustainable practices are key. Without occupant buy-in to sustainable building life practices no progress towards sustainability will be made. The concept of sustainable building use is nothing more than maximizing the life of a building once it is constructed. Many factors can determine how life is maximized but as long as a buildings used life and useful life are close in time sustainability is always a byproduct. Key performance indicators (KPI) such as carbon creation, debris creation by volume, and percent of maxim design life utilized are all metrics identified to be crucial in moving toward the goal of building life sustainability. As time progresses proper building life utilization will either become a standard goal across the industry or the harmful effects from unsuitable construction will continue to rise. Only time will tell to what level occupants and owners of buildings will buy into the idea of achieving sustainability by maximizing buildings' useful life while lowering carbon emissions, lowering debris creation, and increasing financial profitability.

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