Clayscapes: Extracted Landscapes and Circular Futures of the Brick Industry

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A thesis
submitted in partial fulfillment of the
requirements for the degrees of

Master of Architecture
and
Master of Landscape Architecture

University of Washington
2024

Committee:
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Program Authorized to Offer Degree:
Architecture
and
Landscape Architecture

University of Washington

Abstract

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Brick has been a staple of the built environment for over 10,000 years, first appearing alongside our earliest civilizations. The worldwide abundance of clay paired with brick's many positive performance attributes has maintained its relevance across centuries. But it has recently declined in the US as it has faced competition from more affordable building materials, strayed further from its inherent strengths, and received scrutiny regarding its sustainable attributes. However, as the discussion around sustainable design has evolved, the properties of this ancient material have shown the potential to be directly aligned with contemporary circular economy and life cycle design principles. This thesis explores targeted alterations within the full life cycle of brick that would allow the material to achieve its full potential as a durable and adaptable building component that responds to present day environmental challenges. These objectives can be achieved by preserving the embedded energy in historic buildings, restoring abandoned clay mine sites, replacing raw clay with unfired construction waste during brick production, and utilizing alternatives to cement mortar that encourage disassembly. Considerable existing research has successfully developed interventions within each of these themes, but this thesis finds exponential improvement by looking at how these subjects can build upon each other when reviewed in the full life cycle of brick. The research is framed in the context of Seattle, which has a unique history with the material that is reflected in alterations to its surrounding landscape and its stock of historic masonry buildings that are at risk of demolition.

Acknowledgements

This thesis would not have been possible without the support, guidance, and encouragement of many individuals who shaped and enriched this multi-year journey. What began as a studio project grew into a deep and enduring passion, nurtured by an extended community of teachers, craftspeople, friends, and family.

First and foremost, I am deeply grateful to my advisors, Kathryn and Celina, whose guidance, expertise, and unwavering enthusiasm went far beyond their professional obligations. Their encouragement to push boundaries and strive for excellence was a constant source of inspiration.

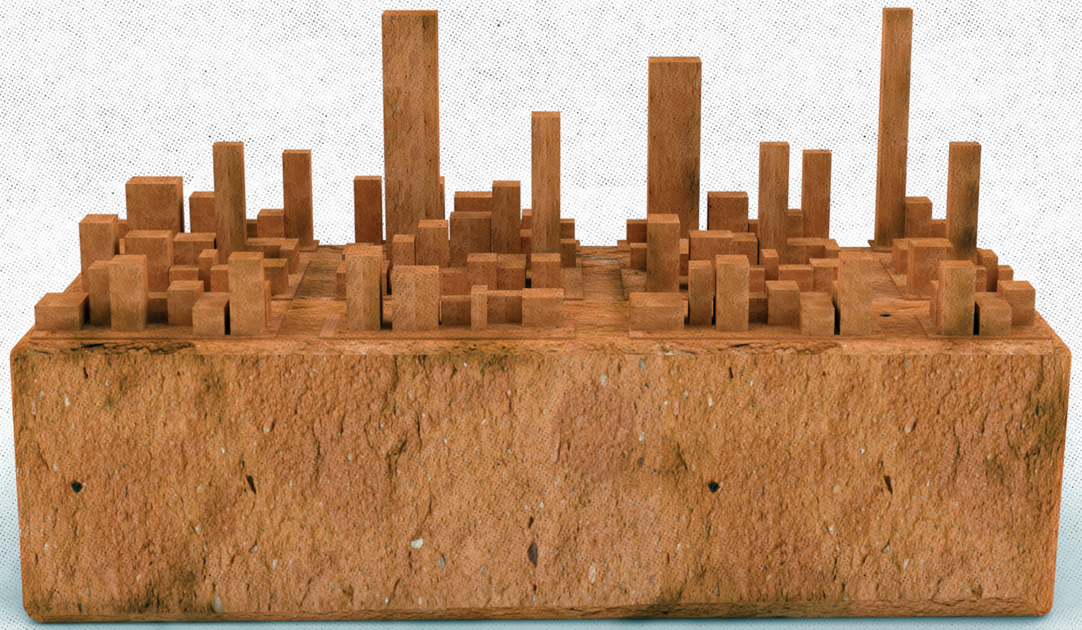
At the University of Washington, I would like to thank Nancy Rottle and Rob Peña for introducing me to Denmark and the world of circular design. Their mentorship laid the groundwork for the earliest ideas that shaped this project. My gratitude also extends to Thomas Bo Jensen, who warmly welcomed me into the Aarhus School of Architecture community. His personal introductions to key figures in the Danish brick industry, including Stig Sørensen from Petersen Tegl and Jørgen Berthelsen, were invaluable to my field research and greatly enriched this work.

I am also indebted to the Valle Foundation, the ScanDesign Foundation, RDH Building Science, and the International Masonry Institute for their generous funding, which enabled me to extend this research across nine countries. Their support not only enhanced the scope of this project but also opened doors for future advocacy and educational opportunities.

Lastly, this work is dedicated to Savannah, whose steadfast love and patience sustained me through moments of inspiration and distress. Her unwavering support during my frequent absences and her ability to ground me in stillness were essential to seeing this journey through to the end.

Clayscapes

Extracted Landscapes and Circular Futures of the Brick Industry



Will Prescott

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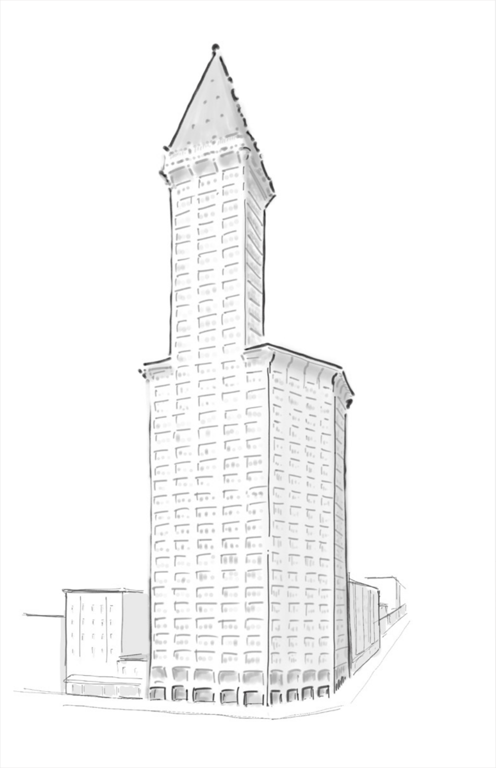
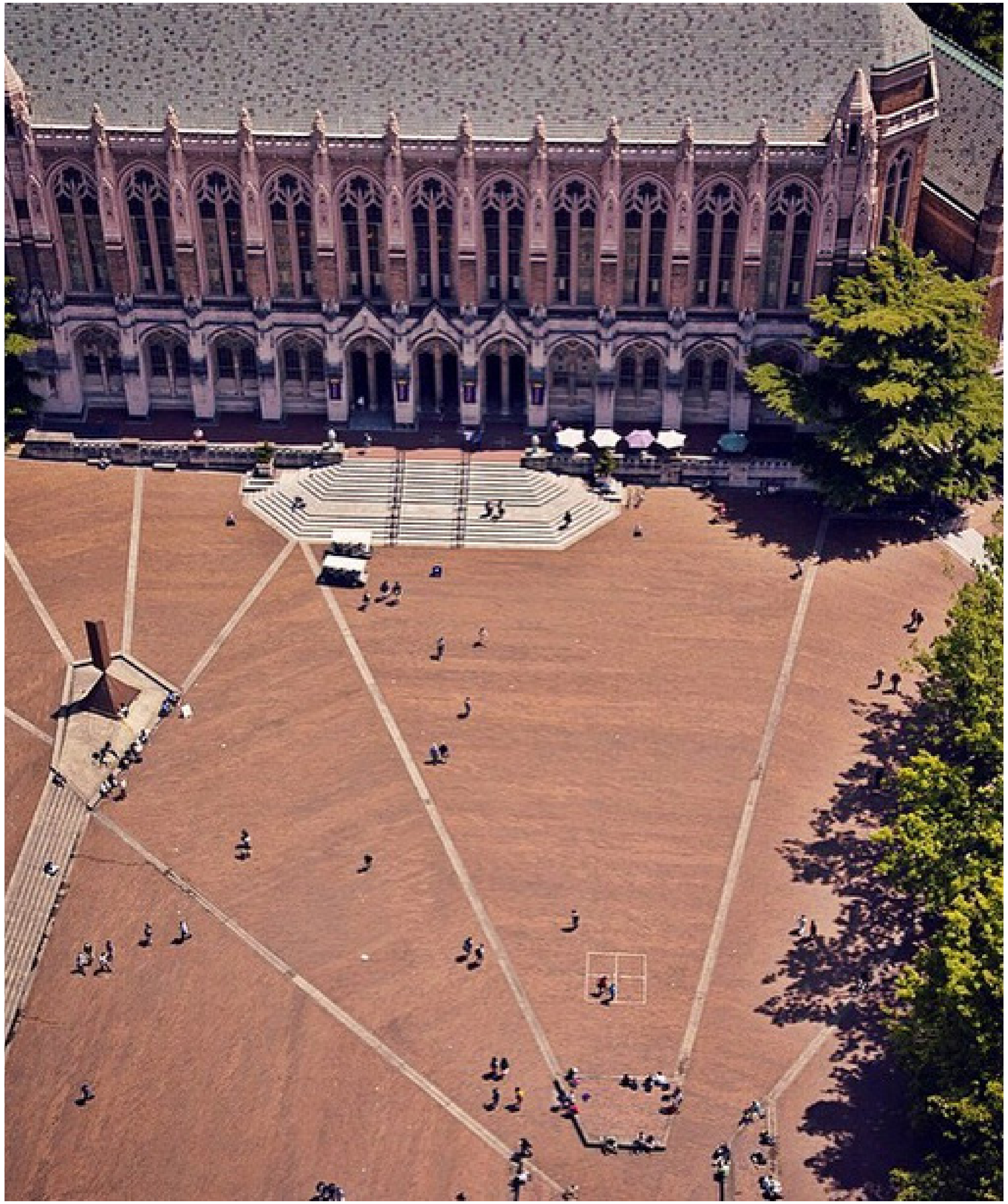


Behind every building...

... lies the shadow of an extracted landscape



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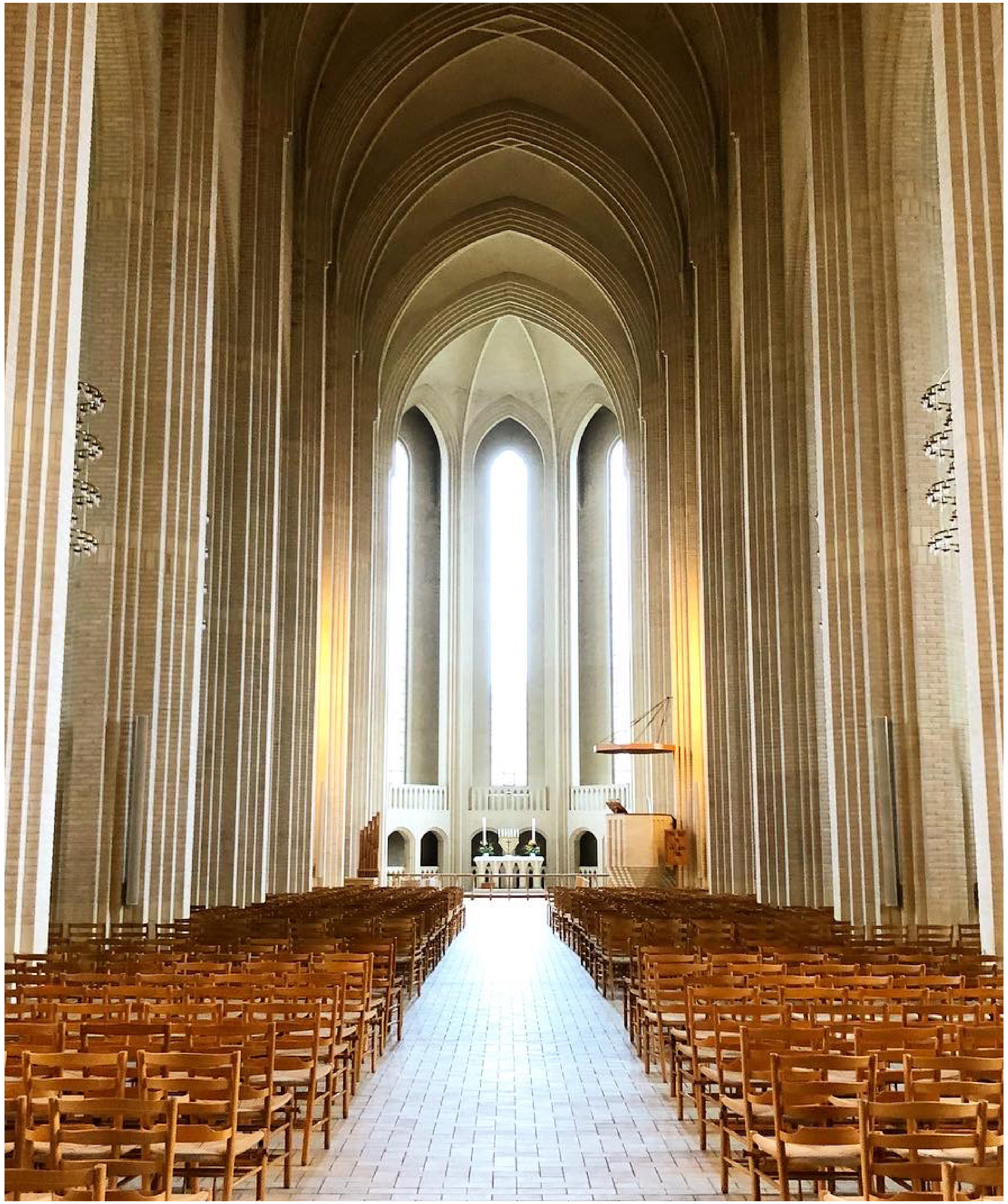

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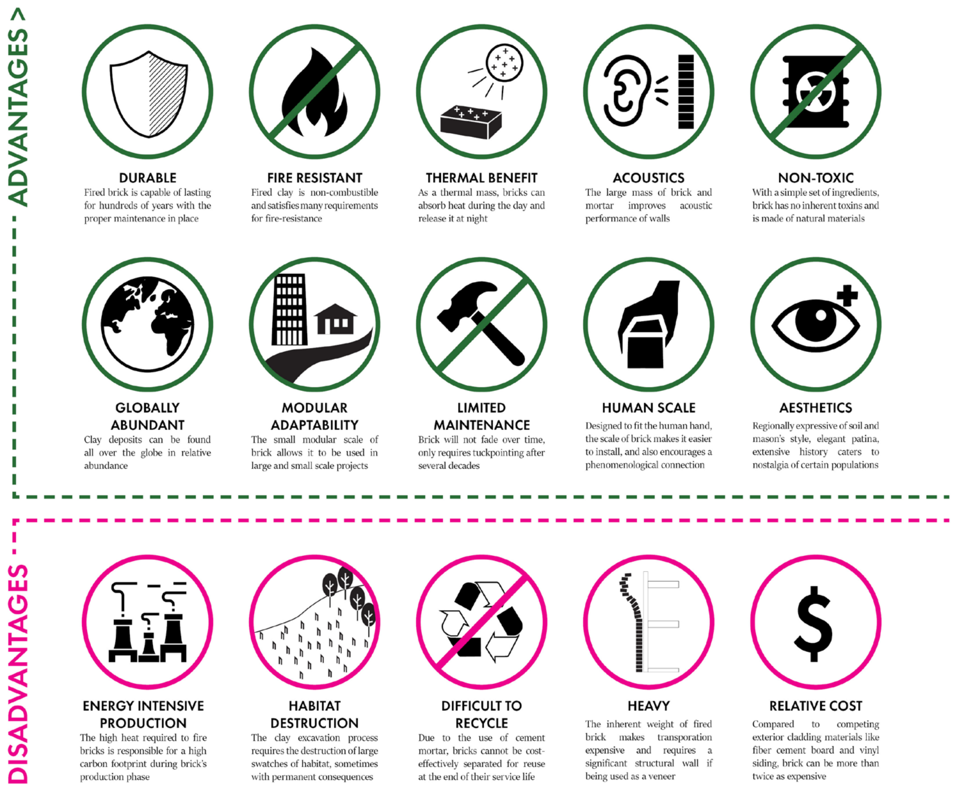


Figure 1.2 *Advantages and disadvantages of brick as a construction material (Diagram by author)*

Chapter 1

Introduction: Searching Backwards for the Future

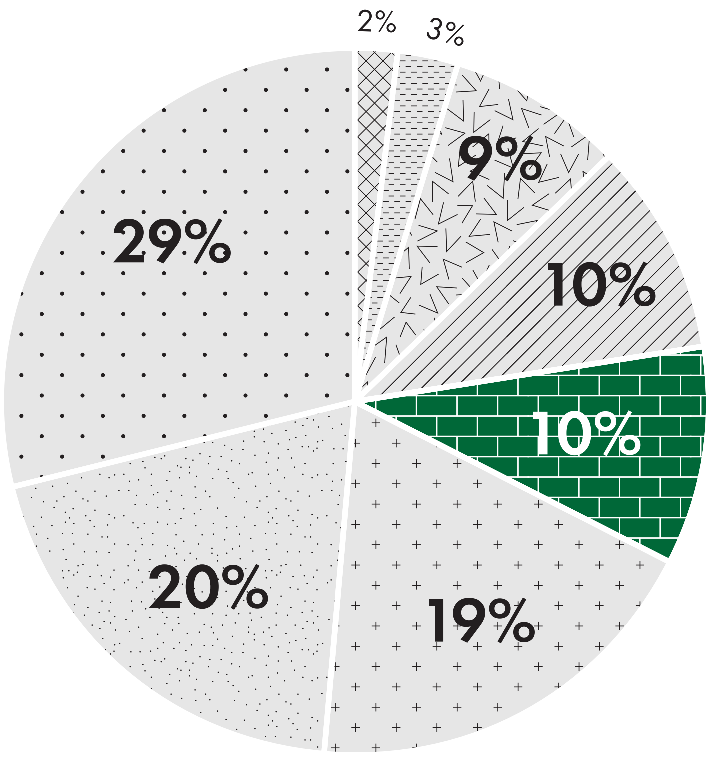
Brick has been a staple of the built environment for nearly 10,000 years, dating back to humankind's earliest cities and civilizations (Campbell 2003). The longevity of brick is due to the many advantages it offers as a building material (Figure 1.2). Fired clay brick has an extensive lifespan and the potential to age gracefully over time with limited maintenance. The modular adaptability of a standardized unit can be repurposed into a variety of forms, from a small paved patio to a 16-story skyscraper. The water resistant properties of clay make it an effective rain screen while also producing acoustic and thermal benefits for residents (Yglesias 2014). Its heat resistant properties made it a material that cities turned to for safety after major fires leveled urban centers (62). Due to the organic and varied nature of clay, each type of brick expresses an individual aesthetic and regional vernacular. And finally, as a simple mixture of clay, sand, and water, the main ingredients of brick are non-toxic and can be found virtually anywhere due to their worldwide abundance (49). Due to these factors, it remains one of the most common construction materials in use today, with over 1.5 trillion bricks produced annually worldwide (Zhang et al. 2018).

However, the United States has seen a downturn in brick utilization alongside the rise of competing materials and a growing awareness of the material's environmental consequences. Fired clay brick, the third most commonly used building material in the world behind concrete and steel, requires extreme and sustained temperatures to manufacture that make it one of the largest carbon emitters in the construction industry (Huang et al. 2020). In addition, the industry's 20th century shift towards cement mortar carries a higher carbon footprint and permanently binds brick together, eliminating opportunities for repurposing this otherwise durable material (Fort and Cerný 2020). And finally, the excavation of raw clay has left scarred landscapes within the boundaries of cities that have grown around them. These former mines pose risks to adjacent human communities and cause irreparable harm to local ecosystems (Cooke and Johnson 2002).

In addition to environmental concerns, the growing popularity of steel and cement-based products through the 20th century eventually supplanted brick as preferred building materials. The evolution of wall construction saw brick masonry transition from a structural material to an exterior cladding as mass masonry walls were replaced by lightweight structural frames. More recent competition has seen cheaper and less labor intensive materials like fiber cement and vinyl siding become the most common exterior cladding in the US (Figure 1.2). Meanwhile, present day brick veneer is often viewed as a historic or nostalgic reference as opposed to a contemporary expression of design. But despite its age, this established material has an opportunity in the 21st century to redefine itself as a material for a sustainable and circular future.

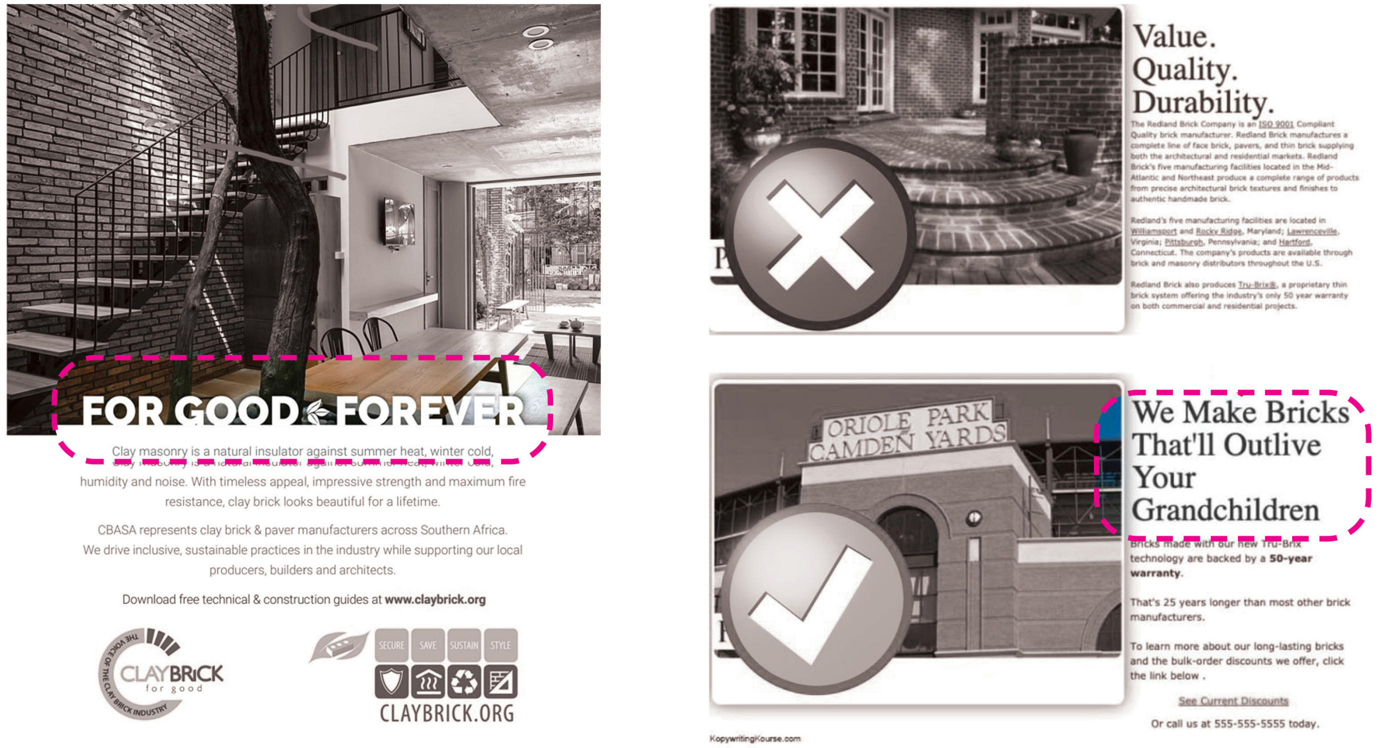
This thesis explores sustainable futures for the brick industry by emphasizing the inherent positive characteristics of brick while addressing the negative environmental impacts it has had on the built environment. Four main research questions are posed in Figure 1.5.

These strategies have been individually pursued by researchers, designers, and restoration specialists across the globe, as documented in later sections of this paper. But there has not yet been a concerted



CLADDING	COST	LIFESPAN
Vinyl Siding	$4-12/sf	30-40 yrs
Fiber Cement	$6-15/sf	50-75 yrs
Engineered Wood	$7-12/sf	30-50 yrs
🟩 Brick	$8-18/sf	100+ yrs
Other	n/a	n/a
Stucco	$7-17/sf	50-80 yrs
Stone	$10-45/sf	30-75 yrs
Block	$11-20/sf	50-100 yrs

Figure 1.3 *Comparison of cladding materials used in the United States, indicating a decline of brick production alongside the rise of alternative cladding materials. (Adapted from Cramer, Kristen. 2024. "2024 House Siding Cost | Average Prices To Reside & Replace." HomeGuide. January 3, 2024.)*



FOR GOOD & FOREVER

Clay masonry is a natural insulator against summer heat, winter cold, humidity and noise. With timeless appeal, impressive strength and maximum fire resistance, clay brick looks beautiful for a lifetime.

CBASA represents clay brick & paver manufacturers across Southern Africa. We drive inclusive, sustainable practices in the industry while supporting our local producers, builders and architects.

Download free technical & construction guides at **www.claybrick.org**

Value.
Quality.
Durability.

The Redland Brick Company is an ISO 9001 Compliant Quality brick manufacturer. Redland Brick manufactures a complete line of face brick, pavers, and thin brick supplying both the architectural and residential markets. Redland Brick's five manufacturing facilities located in the Mid-Atlantic and Northeast produce a complete range of products from precise architectural brick textures and finishes to authentic handmade brick.

Redland's five manufacturing facilities are located in Williamsport and Rocky Ridge, Maryland; Lawrenceville, Virginia; Pittsburgh, Pennsylvania; and Hartford, Connecticut. The company's products are available through brick and masonry distributors throughout the U.S.

Redland Brick also produces Tru-Brix®, a proprietary thin brick system offering the industry's only 50 year warranty on both commercial and residential projects.

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Bricks made with our new Tru-Brix technology are backed by a **50-year warranty**.

That's 25 years longer than most other brick manufacturers.

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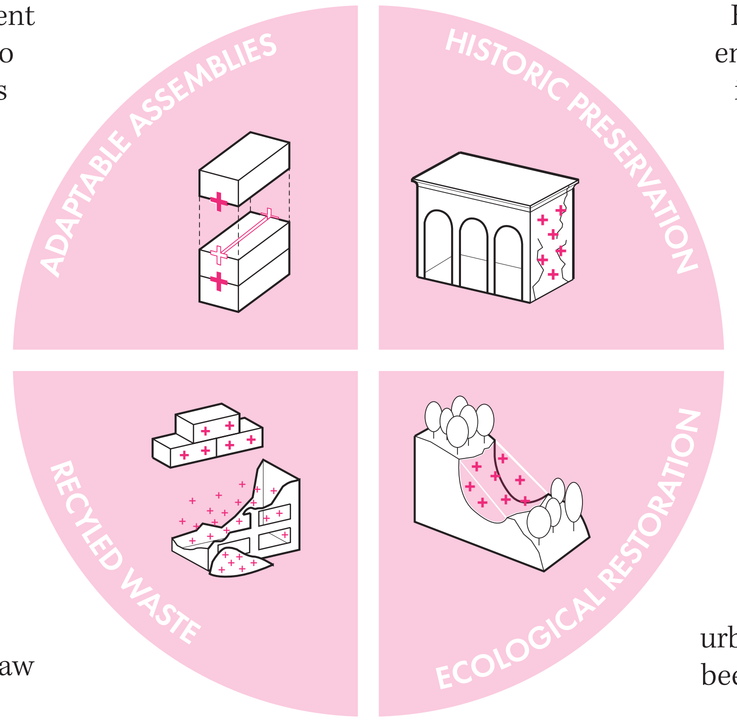
Figure 1.4 *Decline of brick production in the United States alongside the rise of alternative cladding materials (Images courtesy of Clay Brick Association)*



4 How can we revise current construction methods to take advantage of brick's inherent durability and adaptability?

How can we preserve the embodied energy of bricks in unreinforced masonry buildings? **1**

3 How can we alter brick production methods to limit the excavation of raw natural materials?

How can we restore the urban landscapes that have been damaged by historical clay mining practices? **2**

Figure 1.5 *4 primary subject areas and research questions (Diagram by author)*

effort to connect them together as a holistic response to brick's potential for sustainable production. This study will simultaneously consider these four conditions with a focus on the Seattle region, which has a compelling history with brick structures and the extracted clay landscapes from which the material originates.

Adaptable Assemblies: Extending Brick Life Cycles with Details Designed for Disassembly

In response to the construction market shifting towards alternative exterior cladding materials, the brick industry has focused on branding itself as a longer lasting option than its competitors. However, contemporary methods of construction and modern building life cycles deny brick the opportunity to live out its full life cycle. Industry advertising frequently refers to brick as "timeless", built for "future generations", and recyclable (Figure 1.4). The durability and modularity of brick does in fact provide the opportunity for bricks to be repurposed, as a fired clay brick can last for hundreds of years (Nordby et al. 2009). The issue begins with cement-based mortar, today's industry standard, which permanently binds brick together. In contrast, historic buildings utilized a softer lime-based mortar that allowed individual bricks to be collected and repurposed when a building was demolished. Instead, demolished brick buildings with cement mortar are sent to a landfill or ground down and downcycled as aggregate. This requires additional energy inputs, resulting in a net energy loss that eliminates the potential for repurposing this modular material (Nordby et al. 2009).

In order to live up to its full potential life span, brick construction details must allow for simple disassembly in order for the material to last across multiple building life cycles. There are many examples of historic buildings that repurpose brick from previously demolished structures (Figure 1.6 & 1.7). This is because the capable lifespan of a fired clay brick is measured in centuries, as evidenced by many historic buildings that remain standing today (Nordby et al. 2009). But this far exceeds the typical projections for contemporary masonry buildings in North America, which have an average lifespan of just 77.5

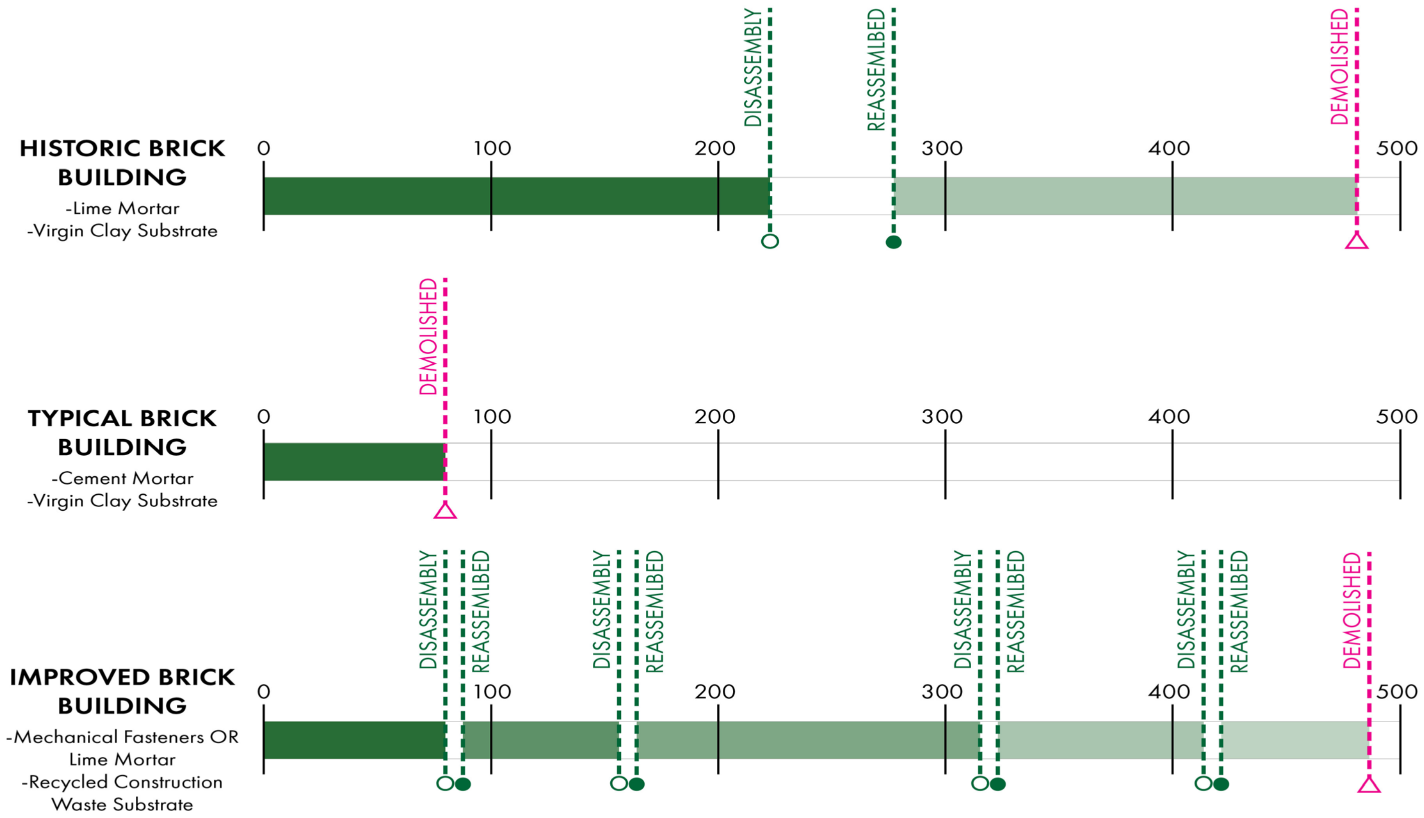


Figure 1.6 *Comparison of brick construction methods and the associated lifespans of the bricks they are composed of. (Adapted from O'Connor 2004)*

Figure 1.7 *(left) Charlottenborg Palace from Kongens Nytorv square in Copenhagen, Denmark. The palace was constructed in the 18th century, but is composed of salvaged bricks from 14th century Kalø Castle in* Figure 1.8 *(right) (Photos by author)*

years (O'Connor 2004). The limited maintenance and durable nature of brick cladding offers opportunities for this lifespan to be extended. But with the increasingly rapid pace of change in building needs and uses, long lasting and adaptable construction materials like brick need to be built for disassembly so that their inherent strengths can be repurposed across multiple building life cycles. This mentality requires a shift in our current methods of brick wall construction that are focused on single building life cycles (Figure 1.6).

Recycled Waste: Replacing Clay with Place-Based-Waste

While the construction detail of a brick wall determines its longevity, the material makeup affects its strength, aesthetics, and immediate environmental impact. Current research into the ecological consequences of mining clay and the widespread availability of non-clay brick substrates indicates that the industry should seek more alternatives to clay-based bricks (Turrión et al. 2021; Zhang et al. 2018). The increasing levels of construction waste in North American cities represents an effective substrate to reduce or fully replace our dependence on raw clay (U.S. Environmental Protection Agency 2018; Zhang et al. 2018).

The abundance of clay within or adjacent to cities is one of the major advantages that led to brick's sustained use. This hyper-local material created a sustainable means of production that required limited transportation between manufacturing and the final construction site in order to be profitable (Glover 1941). But the clay excavation process strips landscapes of their topsoil, flora and fauna, and early unregulated mining practices limited the capacity of abandoned mines to ecologically recover (Zipper et al. 2013). The result is a patchwork of former clay mine sites with dangerous slopes and unhealthy ecosystems dotted across many major American cities. Seattle provides a clear example of this, with many former mines located directly adjacent to residential neighborhoods. This creates a risk for local residents as well as ecosystems, and illustrates the destructive impact that clay mining can have on regional landscapes. As cities expanded and transportation logistics were refined through the 20th century, clay mines were pushed further away from city centers. Bricks are now delivered further than they were previously, limiting the hyper local advantage that the material once boasted.

Decades of research has indicated that growing waste streams in urban areas provide adequate alternatives to clay as the primary substrate material in brick production (Zhang et al, 2018). The relatively short life spans of buildings in the United States results in a growing amount of demolished buildings, resulting in massive amounts of construction debris. Over 600 million tons of landfill waste is annually generated by the construction industry in the United States, more than twice the amount produced by entire municipal waste streams (U.S. Environmental Protection Agency 2018). By repurposing this refuse as a building material, the amount of virgin clay required for brick production can be reduced and waste can be diverted from overburdened landfills.

While there has been individual research towards repurposing industrial waste material as brick substrate (Zhang et al. 2018) and some products that provide alternatives to cement mortar, they have not been considered within a single study. By considering these two strategies simultaneously, the environmental impact of brick production, construction, disassembly and reuse can be more effectively managed across the full life span of the material.

Historic Preservation: Unreinforced Masonry Buildings in Seattle

A full life cycle analysis of the brick industry should not only account for the bricks that we produce in the future, but also management of the material that has already been produced. While there are many exciting opportunities on the horizon to drastically redefine the historically energy intensive method of producing bricks, this is looking past the embedded energy that already exists within our current stock of aging masonry buildings. By preserving and extending the life cycles of these existing buildings we can avoid additions to landfills and in many cases preserve the character of densifying neighborhoods.

Seattle, the largest city in the Pacific Northwest, has historically been known as a timber town due the region's vast expanses of forest. Less well known is the fact that within the past century it was also one of the world's leading producers of brick pavers, and it has an extensive and reputable selection of masonry

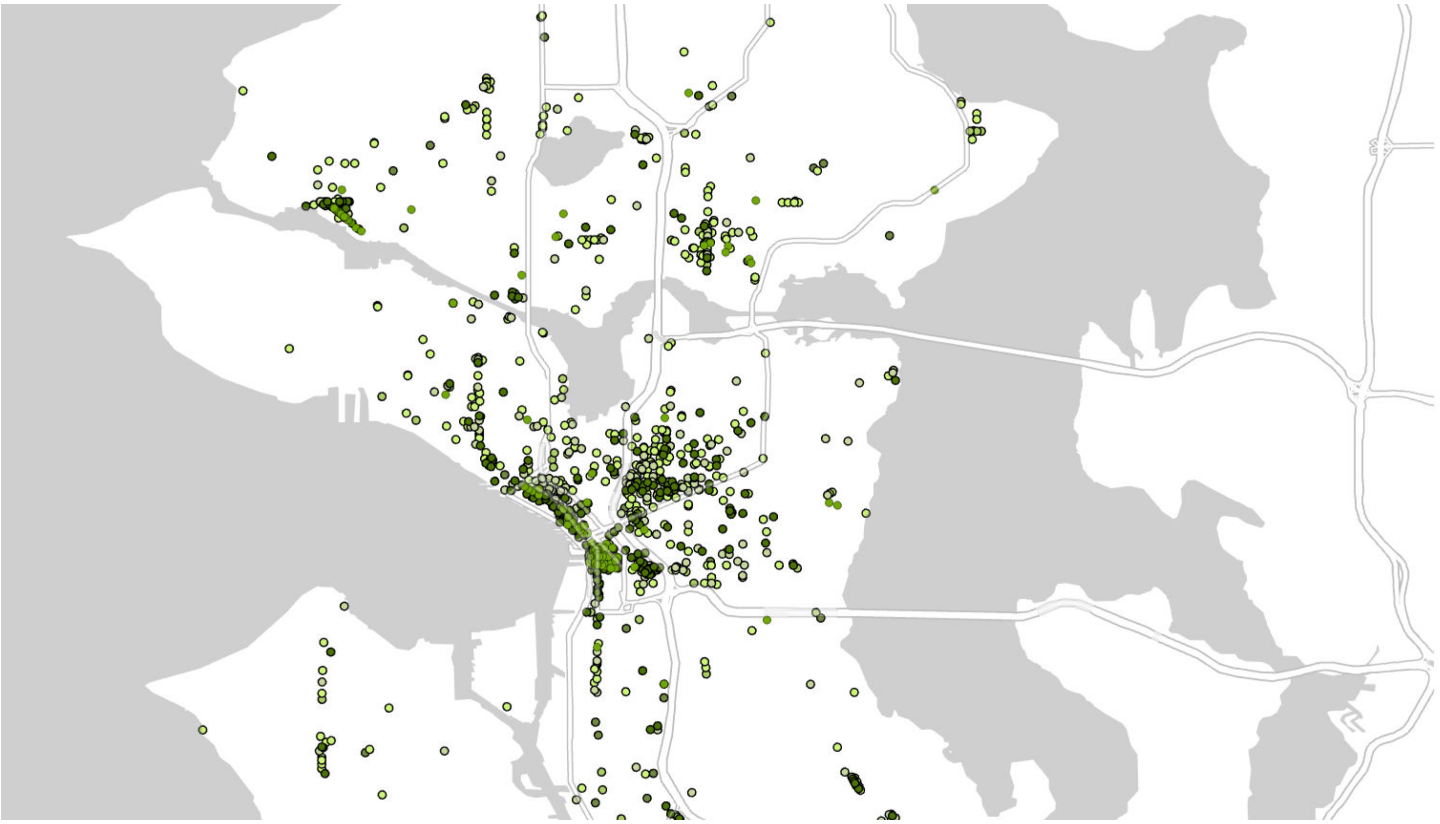


Figure 1.9 *Unreinforced masonry (URM) buildings in Seattle. (Adapted from "Unreinforced Masonry Buildings | City of Seattle Open Data Portal." n.d. Accessed December 1, 2024.)*

Figure 1.10 *Former clay mines in the Duwamish River Valley of Seattle. (Adapted from "Mines and Minerals Database." Washington Department of Natural Resources. August 2023.)*

buildings. In the present day, many of the heritage buildings from the region's early 20th century apex of brick production are at risk of demolition due to their structural liabilities spurred on by another regional specialty: earthquakes.

There are more than 1,100 unreinforced masonry buildings in the city, which are particularly vulnerable during seismic events (Figure 1.9). There are several options for seismic retrofits that can improve the safety of these structures, but they are often too costly for building owners to implement (Beekman and Gilbert 2020). Legislation efforts are on the horizon in Seattle that would make such retrofits mandatory, which could result in owners choosing to demolish their buildings and sell their land rather than find the resources to upgrade their properties. In order to preserve the embedded energy within historic buildings, there must be legislation that provides sources of funding to help pay for retrofits and extend their operable lifespan to match that of their exterior envelope ("Preserving and Retrofitting Seattle's URM Buildings" 2023).

Ecological Restoration: Urban Clay Mines

The preservation of existing buildings is intertwined with the restoration of the clay mines from which the material was originally excavated. When considering the full life cycle of a material, the excavation phase of the manufacturing process expels a great amount of energy while also limiting the capacity of the excavated landscape to recover and provide future ecological benefits. Surface mining for clay reserves is a particularly devastating manufacturing process that can result in irreparable damage to the environment (Cooke and Johnson 2002).

This is the case for the clay mines along Seattle's Duwamish River Valley, which provided Seattle with its initial supply of bricks as the city expanded in the late 19th century. The steep grades created by mining activity and the clearing of existing topsoils resulted in areas that prevented future development, created fall risks to residents, and limited the ability for native plants to reestablish. Investment in these areas could result in more balanced ecosystems that can provide important wildlife habitat and green infrastructure benefits for the city. In order to pursue restoration of these sites, they must combine strategies that provide slope stabilization, soil restoration, non-invasive plant integration, and continued maintenance.

1.1 Thesis Proposal

In summary, this thesis considers a sustainable future for the brick industry that confronts the full life cycle impacts of both new and existing brick material. The topic is researched through four strategies that limit the use of energy and material in construction; construction waste as an alternative to virgin clay extraction, adaptable construction techniques that extend the operable lifespan of individual bricks, preservation of existing brick buildings, and best practices for restoring the abandoned clay mines in Seattle (Figure 1.5)

Scope of Research

The first section begins with a brief summary of brick's evolution through history, tracking how its uses have evolved to the present day. The historical review concludes with a focus on the Seattle region, developing an understanding of the brick industry's connection to the social, economic and environmental history of the city.

This is followed by a review of the processes and impacts of clay excavation. It covers the types of clay that are harvested for brick production, common methods of excavation, and how mining operations impact local soil, plant and wildlife communities.

The brick production industry is then reviewed, beginning with an illustration of brick-shaping methods and manufacturing processes. The section concludes with a study of brick wall assembly details, revealing the modern construction techniques that limit brick's ability to be repurposed.

Next, a series of existing case studies are presented to illustrate positive changes that have occurred in the brick industry. Examples of relevant mining sites are reviewed to assemble best practices in the restoration of clay mines. Innovations in brick production are highlighted through a survey of contemporary bricks that repurpose construction waste in the place of clay. Alternative brick construction details are then explored through examples of adaptable brick wall assemblies.

Deliverables

Through this research, an understanding of current industry practices and their impacts on the built and natural environment is presented. In response, the paper concludes with a series of theoretical recommendations for the industry to consider as steps towards a more sustainable future.

First, a toolkit of clay mine restoration techniques provides strategies for land managers to implement on areas that have been impacted by the clay mining industry. This thesis has revealed a lack of research specifically targeting abandoned urban clay mines, and the toolkit aims to create a starting point for those seeking to restore a site. These techniques are a conglomeration of successful actions employed at similar post-industrial mine sites and regulations that have been released by local government organizations.

This is followed by a study combining alternative clay substrates and adaptable brick wall assemblies to create physical mockups of brick walls. This "idealized" brick wall is a physical representation of research that has individually pursued alternatives to virgin clay extraction and construction techniques that facilitate disassembly to take advantage of brick's durability across multiple building life spans. Repurposed gypsum construction waste and locally sourced oyster shells from the marine industry are implemented as alternative substrates to clay, and mechanical fasteners are used in lieu of permanently binding cement mortar.

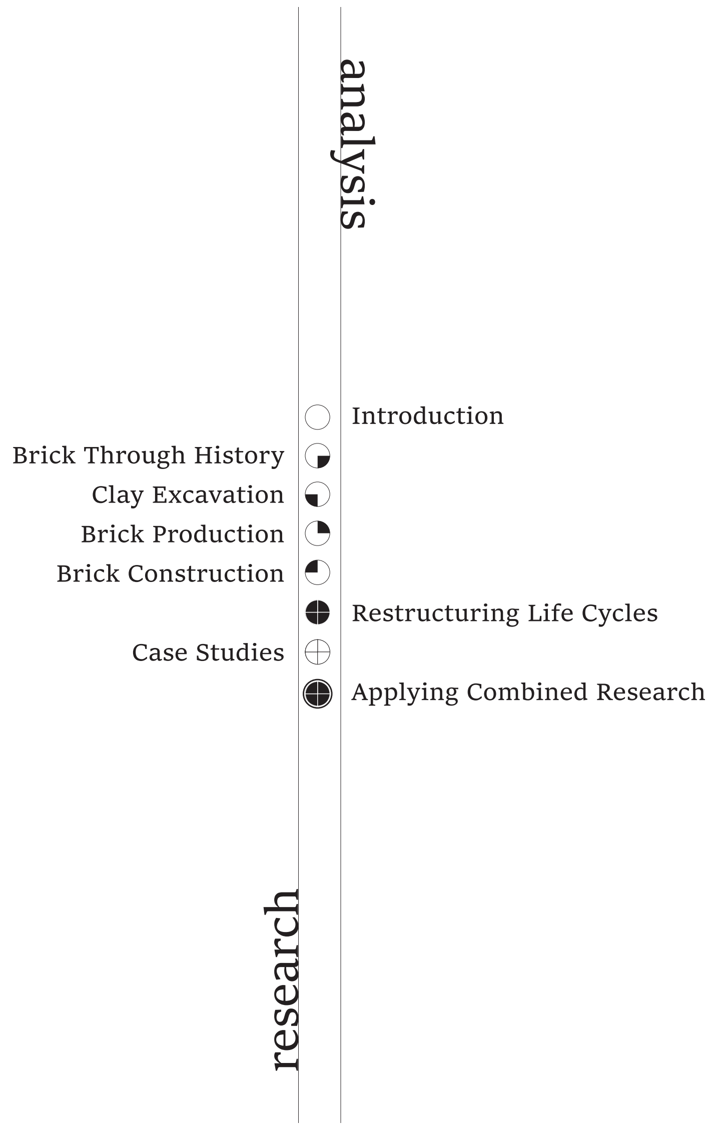


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Figure 2.1 *The Baths of Caracalla in Rome, Italy date back to the 3rd century CE and prominently feature brick construction methods of the time period (Photo by author)*

Chapter 2

Brick Across History

As with any pursuit of history, a better understanding of the past can lead to more informed decisions about the future. This is no different with brick, which is a simple material that has gone through many cycles of development and personalization from early history to the present day. A full review of brick's history is an exhaustive undertaking worthy of its own book. This review instead focuses on the major innovations across brick's many years of development, emphasizing how past methods of construction and production have impacted the current practices of the industry.

2.1 WORLD HISTORY

Ancient Innovations

The history of brick begins with the origins of recorded civilization, appearing alongside our first cities as humankind shifted from the lightweight and nimble needs of nomadic living to durable and fortified permanent settlements. The first recorded use of mud brick came around 8,000 B.C. in Jericho, located in the present-day West Bank along the River Jordan (Campbell 2003). These were relatively inconsistently sized lumps of mud that were dried in the sun before being stacked to make a wall. In 3,500 B.C., the advent of the brick mold in Mesopotamia represented the first major jump in brick technology (28). Wooden molds with flat, parallel faces were filled with mud, compressed by hand, and excess mud was scraped away across the top of the mold (See Figure 2.2). While a simple technique, it is the genesis of the same method used today for hand-pressed bricks. This method was exported to Ancient Egypt, where it was further developed into brick arches to allow for wider spans (29).

8300 - 7600 B.C.E.
The first known use of sun dried bricks appear in Jericho, utilizing mud for mortar

5900 - 5300 B.C.E.
Brick molds introduced, resulting in more evenly shaped masonry and more precisely built structures

5000 - 4500 B.C.E.
Fired brick appears in Mesopatamia, creating stronger masonry that is resistant to rain. Developed alongside pottery

1st CENTURY
Romans refine existing methods, using brick as cladding material for concrete-like interior structure

19th CENTURY
Industrial revolution mechanizes the brickmaking process, increasing output and improving quality

Figure 2.2 *Timeline of technological highlights in the global history of brick*

Mesopotamia again is responsible for the next major breakthrough, with the innovation of the fired brick appearing in the Uruk period between 3,100-2,900 B.C. (30). Fired brick requires the sophisticated knowledge of heating brick to an ideal and replicable temperature, between 950 and 1150 degrees celsius, for an extended period of time (30). If heated to a higher temperature, the clay turns into a misshapen glass-like material. When fired too cold, the resulting brick is too brittle. This represented a far more advanced understanding of an early industrial process. The result was a more stable and waterproof product that could survive outside of arid desert climates through repeated precipitation events. Over the next 2,500 years brick technology spread throughout the Middle East and Mediterranean regions, with the city of Babylon developing glazed brick around 600 B.C. (35). This process coats bricks with a liquid slurry prior to firing, producing an array of colorful and expressive finishes while also improving reducing water permeability.

These developments were eventually exported further around the less arid regions of the Mediterranean, with the technique of firing brick eventually adapted by the Ancient Greeks to produce terracotta roof tiles between 2,600-2,000 B.C. (42). The durability, weather resistance, and standardized dimensions made fired clay the ideal material for these roofing applications. While these clay products were found throughout the region, fired brick as a structural wall component was rare due to the high cost and level of expertise required to produce it. Mud-brick, stone, and wood wall construction was more prevalent in a region with better access to forests than the original brick innovators in the Middle East.

Roman Brick

The Romans also originally restricted their use of fired ceramic materials to roof tiles until the first century B.C. (43). Prior to this, bricks were primarily sun-dried adobe, bound together by mud mortar and laid over stone foundations to limit cracking of the brittle material (Labate 2016). However, in the ensuing centuries the technology became far more prevalent and refined as the Romans continued to experiment with firing techniques. While the Greeks were the original Europeans to introduce fired brick to the continent, it was the Romans who were responsible for eventually sharing and refining the process across their growing empire (46).

The Romans experimented with many different methods of brick wall construction, pushing beyond the traditional method of simply stacking bricks on top of one another to form a structural mass wall. Instead, they used bricks as a facing material, similar to the contemporary use of brick in veneer wall systems. Roman brick construction after the 1st century CE was typically an envelope of facing brick with an interior structure composed of fist-sized stones set in generous amounts of mortar. The brick created a more waterproof and reparable alternative to exposed concrete walls, which were susceptible to cracking (50). The relatively consistent and clean dimensions of brick also made it ideal as a setting course within a wall made of cheaper materials, such as rough hewn stone. This is particularly important in areas like arches that require additional precision. Lime mortar, made from a combination of burnt limestone, water, and mineral additives known as "pozzolans", was used to bind the masonry together (50). This was an upgrade from earlier brick construction that relied on mud slurries for mortar, as it was stronger, dried quickly, and could cure underwater.

The Romans are now well known for their use of brick in projects such as The Colosseum in Rome (completed in 80 A.D.), long spanning civil engineering projects like aqueducts, and the later Byzantine works such as the Hagia Sophia in Constantinople (completed in 537 A.D.). But after the disintegration of the Roman Empire, brick construction notably declined in Europe (78). As brickmaking had been the task of Roman soldiers, this skill was not passed on to the inhabitants of the territories they occupied (78).

Figure 2.3 *Remains of a brick and stone wall system at the Roman theatre complex of Fourvière in Lyon, France, dating back to the 1st century B.C.E. Square shaped bricks were used here as setting courses between wider masses of stone set in concrete, taking advantage of the fired material's more precise dimensions in complicated construction areas like the archway shown here (Photo by author)*

Cross Cultural Adaptations

While the early architecture of the United States was primarily influenced by Western European historical precedents, developments in brick manufacturing and construction in countries outside of Europe were making similar strides that would equally impact global expressions of brickwork (Almssad, Almusaed, and Homod 2022). For example, the Aztecs separately pioneered the use of adobe brick in the 15th century, prior to the arrival of European explorers. Elsewhere in Central America, the Pyramid of the Sun in Teotihuacan rivals the Great Pyramids of Giza in scale. In Asia, the Chinese were developing their own brick technology as far back at 1000 B.C., although it is unclear if the knowledge was imported from Mesopotamia or created on their own (Campbell 2003). They had notably different methods, developing a wider range of brick sizes and the use of different kilns (Liu and Zhang 2020). For example, a distinctive "blue brick" was widely used throughout China, the result of a lower firing temperature in a de-oxygenated environment. Distinctive brick patterns continued to be developed by the expanding Islamic nations and the ornately constructed Buddhist temples in modern day Myanmar (Campbell 2003). Variations in clay types and firing methods from each of these regions is expressed in the resulting projects, with great variations in color, texture, and strength that were said to achieve "a level of mastery in the ornamental, creative and aesthetic use of bricks that has not been paralleled" (Almssad, Almusaed, and Homod 2022).

While this period saw variations in brick construction techniques and aesthetic expressions across the globe, there was relatively limited change in the basic manufactured components of the material. But in all cases, brick remained a material reserved for buildings of distinction, as the process was costly and required sophisticated knowledge. Chinese type printing in the 11th century and the advent of the printing press in 14th century Europe helped to spread the knowledge of brick building, but it wasn't until the Industrial Revolution in the 19th century that brickmaking would see another major technological leap.

Industrial Revolution

The rapid rise of new industries in the 19th century led to greater access to raw materials, as well as an increased need for construction components to build factories and housing for a growing population. A series of technological innovations in the brickmaking process, as well as the speed with which they were shared across the world, led to a rapid rise in global brick production throughout the century.

The traditional methods of brickmaking had not seen dramatic changes since the Mesopotamians developed fired brick in the 4th century B.C. For example, clay was excavated and sorted by hand, then kneaded with feet before it was set into handheld molds for drying and firing (Almssad, Almusaed, and Homod 2022). During this period, a brickmaker was typically expected to be able to make 1,000 bricks by hand each day (Campbell 2003). Early versions of mid-19th century pressing machines increased the average daily output to 30,00. During the Industrial Revolution, all elements of production - clay excavation, brick molding, and firing - were facilitated by mechanized processes that made the process cheaper, faster, and less laborious. By shifting away from a handmade product and towards a mechanized process, the dimensions of brick also became more consistent. With this simplified and streamlined manufacturing process, brick became a cheaper, standardized, and more readily available material that was no longer restricted to wealthy building owners. Industrial buildings capitalized on the fire-resistant properties of brick in order to manufacture materials that required extreme temperatures to produce, such as iron foundries. Refractory brick - composed of a specific clay with high silica and alumina content that provides improved fire-resistance - became a commonly used material for industry and chimneys (Almssad, Almusaed, and Homod 2022). These fire resistant properties became more essential in increasingly congested urban centers, where fire walls between buildings could be a deterrent to the spread of fires. However it should be noted that brick was the most successful as an envelope material that worked in conjunction with heavy timber structural frames. The structural advantages of brick lies in its compressive strength, and while the Romans demonstrated that great spans could be made via arches in their aqueducts, the combined weight and material cost of this construction process was prohibitive. By combining the tensile strength of timber for wide spans with the compressive and water resistant properties of brick on the exterior envelope, the advantages of both materials were emphasized.

Evolution of Brick Wall Details

Present-day brick wall assemblies are visual allusions to historic brick construction methods. Much of this can be attributed to nostalgic preference for materials that reference historic architecture. These historic styles have historically fluctuated between a structural and a veneer material.

Earlier solid load-bearing masonry walls were composed of bricks that were more porous than present day materials. This was due to rudimentary and uneven firing methods that resulted in higher absorption rates. The porous nature of the material allowed water to make its way through the brick modules. The mortar used at the time, composed mainly of lime, was more flexible and porous than the brick, which allowed water to travel through these joints. In effect, the wall was able to "breathe" and dry itself out.

Later designs continued to emphasize moisture wicking properties of walls with the advent of cavity walls by the British in the early 1800's. Cavity walls provide gaps between the exterior and interior wythes of masonry in order to create a continuous vertical shaft through the assembly that encourages leaching water to drop through the interior of the wall and out via weep holes at the base of the assembly (Figure 2.4). These walls were still serving as both exterior veneer and structural support, held together by courses of alternating rotated bricks that tied the assembly together.

20th Century United States

The rapid increase of brick manufacturing technology during the Industrial Revolution paved the way for the 20th century to see the highest amount of brick used in history (Campbell 2003). While it is common to equate the rise of Modernism with the use of "contemporary" materials such as steel, concrete and glass, brick was still an essential construction element throughout the century. Much of this was due to the massive destruction caused by two world wars, necessitating the rapid reconstruction of major cities. Many of the large housing projects developed after the Second World War utilized brick as their main envelope material.

But the 20th century also saw brick construction shift almost entirely from structural bearing walls to exterior rain screen veneers supported by an interior structural backing wall made of another material, like concrete or steel (Figure 2.4). These alternative structural walls could be constructed in less time and often in more lightweight assemblies than traditional mass masonry walls. This effectively cut the need for bricks by more than 50%, as it was no longer needed to perform both as a structure and envelope. The transition away from structural brick walls is directly reflected in the reduction in brick manufacturing facilities, a stark change seen in the United States and abroad throughout the 20th century. While brick production had historically been intrinsically linked to the region where it was produced, the decrease in manufacturers along with improved transportation logistics led to brick being shipped further from its point of extraction than ever before. In doing so, the regional specificity of the material eroded over time.

Among the manufacturers that still remain, brick production has nearly become an entirely automated process (301). Much of this contemporary manufacturing technology is based on the innovations that occurred in the 19th century, but with greater levels of precision and automation. Refinements have also been made in the manufacturing process with specific additives that can increase the compressive strength and water resistance properties of brick (Zhang et al. 2018).

The major threat to brick production has been the rise of concrete and cement block structures (Campbell 2003). While concrete has the ability to produce a stronger, cheaper, and more adaptable option than dimensionally limited brick buildings, it has an inherently high embodied carbon footprint that now accounts for 6% of the entire Earth's carbon emissions (Yglesias 2014). The production of cement requires a higher heating temperature through multiple stages of firing. Concrete's ubiquity and often "plain" or "grey" aesthetic has also resulted in a somewhat negative public opinion, as evidenced by the "concrete jungle" nickname used to describe rapidly developed cities (5). And while poured concrete provides an array of options that allow designers to sculpt buildings like a softened clay, the end result has limited recycling opportunities outside of crushed aggregate. Despite the issues of its major

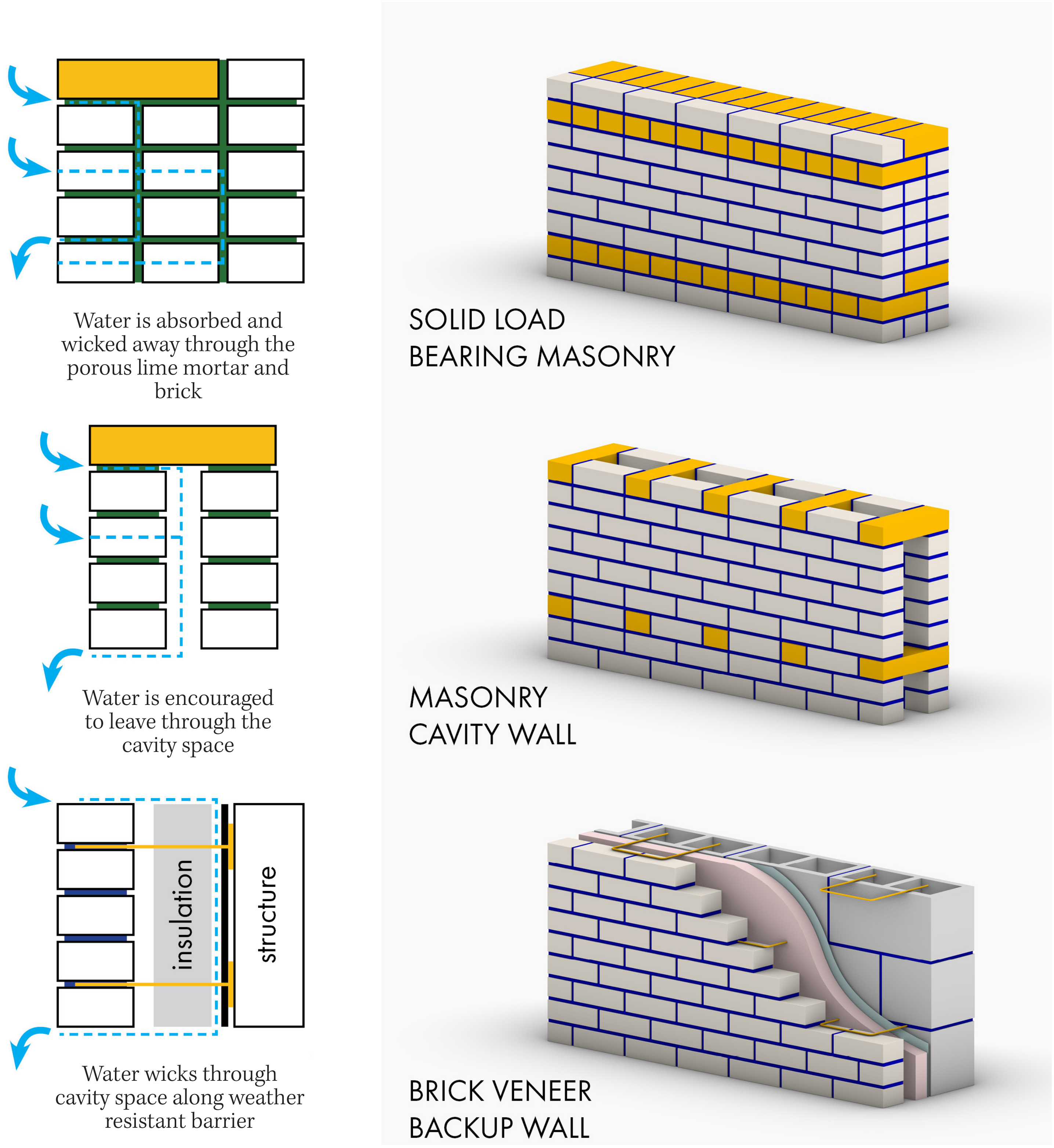


Figure 2.4 *Evolution of brick wall details and their methods of handling water infiltration, from the earliest load bearing masonry walls to present-day brick veneer systems (Diagrams by author)*

PRE-COLONIAL
Buildings were mainly lightweight wood structures, working with the abundant timber in found throughout the region

1889
The Great Seattle Fire destroys a large portion of the downtown. New building codes require brick exteriors and party walls. More than one dozen brickmakers facilities soon emerge

1917
Denny-Renton Clay and Coal Company becomes the world's leading producer of brick pavers, utilizing large reserves of refractory clay found alongside coal seams in the area

1949, 1965, 2001
Earthquakes rattle the region, with particular damage to unreinforced masonry structures (URMs) built in the years before stricter building codes

2008 - present
Seattle City Council pushes to require URM's to be retrofitted. Bill has been through several rounds of review, with the latest projections targeting enactment in 2025

Figure 2.5 *Major events within the timeline of Seattle's brick history*

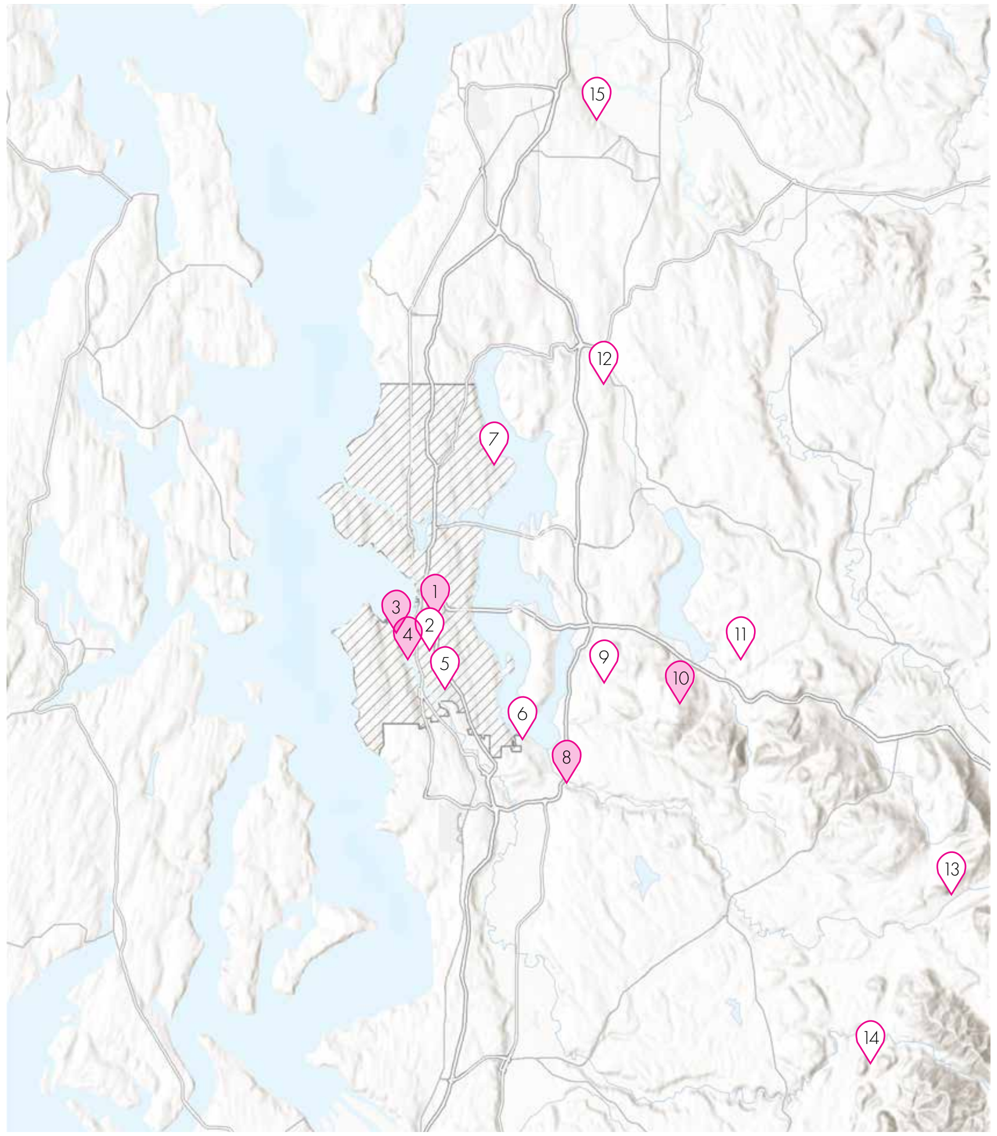
competitor, brick use has continued to decline in the United States, from 7 billion units in 1995 to 5.1 billion in 2008 (Man 2019). Along with this decline in brick production has been a reduction in masonry apprenticeships and the sharing of skilled knowledge from generation to generation (Campbell 2003). Much like the years after the decline of the Roman empire, there is a risk that the past knowledge of skilled craftsmen will be lost to future builders.

2.2 SEATTLE HISTORY

As with other large cities such as London, Chicago, and San Francisco, Seattle turned to brick after a large fire reduced much of its central business district in 1889 (Klingle 2007). This provided the city with an opportunity to revise their building regulations and develop new standards for fire safety in a rapidly densifying urban core. This meant that brick production in the area would need to increase to keep up with the growing demand. In response, additional clay pits were excavated in several nearby locations. As the city expanded and the clay deposits dwindled, the locations of the mines expanded further out from the city center (Figure 2.5).

Early clay pits and brick manufacturing facilities that took off immediately after the fire included Builders Brick Company in Beacon Hill, Pontiac Brick and Tile Company in Sandpoint, and the Denny Renton Coal and Clay Company (Figure 2.5). The Denny Renton Coal and Clay Company became very popular in the early 1920's, reaching its apex in 1917 when it produced 58 million bricks, allowing it to declare they were the world's largest producer of paving bricks (Warren 2014). Their clay production was mainly drawn from deposits along the banks of the Duwamish River, from a hillside clay pit in the now derelict town of Taylor, and from shale deposits along the south riverbanks of Lake Washington. The company has sustained success through the early 20th century, providing the paving material for many of the roads across the Pacific Northwest. They were even known to have shipped material across the United States and abroad, sending brick pavers as far as Tokyo, India and South Africa. But the ensuing shift towards asphalt as a paving material in later years led to their steady decline. The company was eventually bought out and shifted towards other industrial material production (Hilding 1991). There is limited evidence about who worked at these facilities, but census data reveals that many of these laborers were young European immigrants who had recently arrived in the United States.

In the present day, only Builder's Brick Company, now known as Mutual Materials, remains as a functioning brick producer in the Seattle area (Burkitt 1999). In fact, Mutual Materials is now the only primary producer of brick remaining in much of the northwestern United States (Man 2019). They were originally located near the center of the city, with a clay pit and brick production facility located in the current Beacon Hill Greenbelt. However, they were evicted



① BUILDER'S BRICK CO.
9th Ave S & Charleston, Seattle

② SEATTLE BRICK & TILE CO.
9th Ave S & Andover, Seattle

③ LOHSE BRICK COMPANY
W Marginal Way, Seattle

④ ABRAHAMSON BRICK CO.
W Marginal Way, Seattle

⑤ DENNY CLAY CO.
E Marginal Way, Seattle

⑥ ADDERSON, J.G.
Crestwood Drive S, Seattle

⑦ PONTIAC BRICK & TILE CO.
57th Ave NE, Seattle

⑧ RENTON CLAY WORKS
Cedar River Trail, Renton

⑨ MUTUAL MATERIALS
Coal Creek Parkway, Newcastle

⑩ MUTUAL MATERIALS CLAY PIT
Cougar Mountain, Renton

⑪ HARRIS CLAY PIT
Issaquah

⑫ NW HAYDITE COMPANY
Woodinville

⑬ TAYLOR CLAY MINE
Cedar Falls Road, Bagley Junction

⑭ PALMER CLAY PIT
Bayne Junction

⑮ SHAFFER BRICK & TILE CO.
109th St SE, Everett

Figure 2.6 *Below: Map of brick manufacturers in the Seattle metropolitan region. Above: Bricks found on site of former manufacturing facilities highlighted in the map (Image by author)*

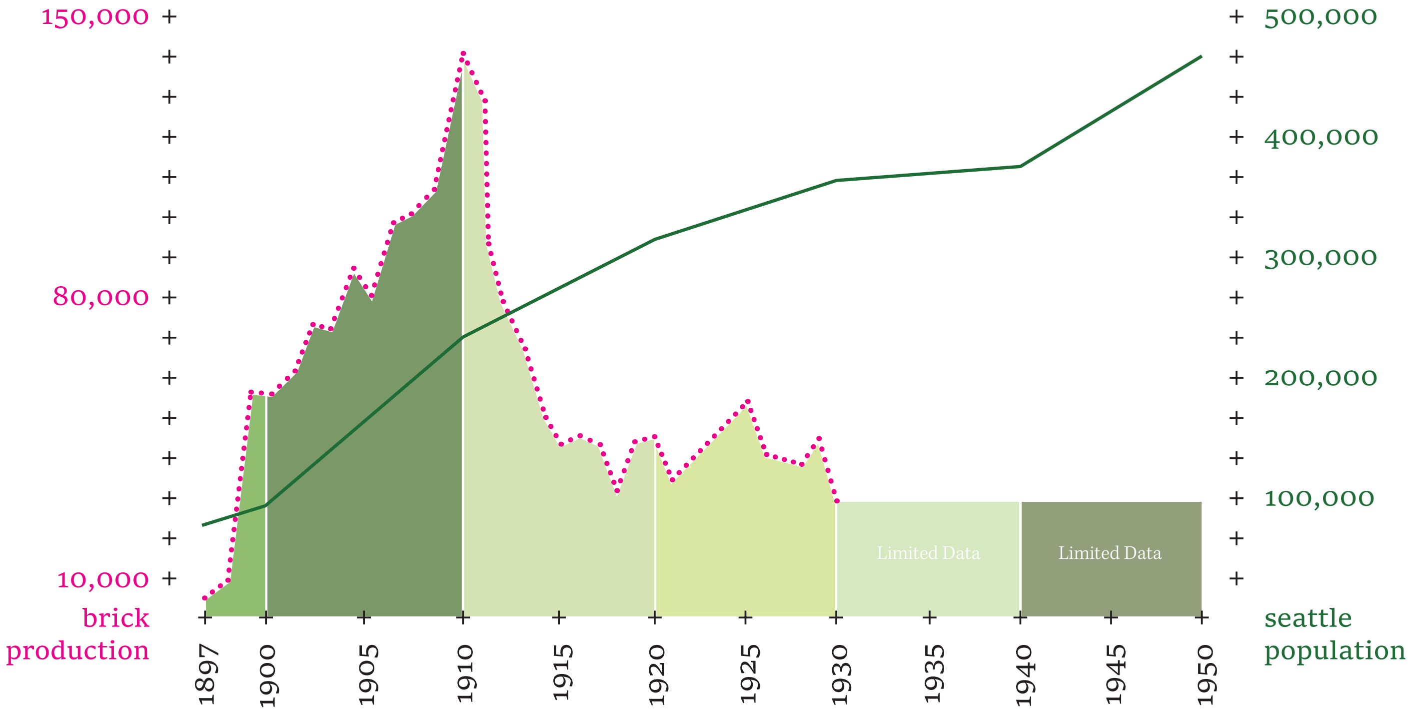
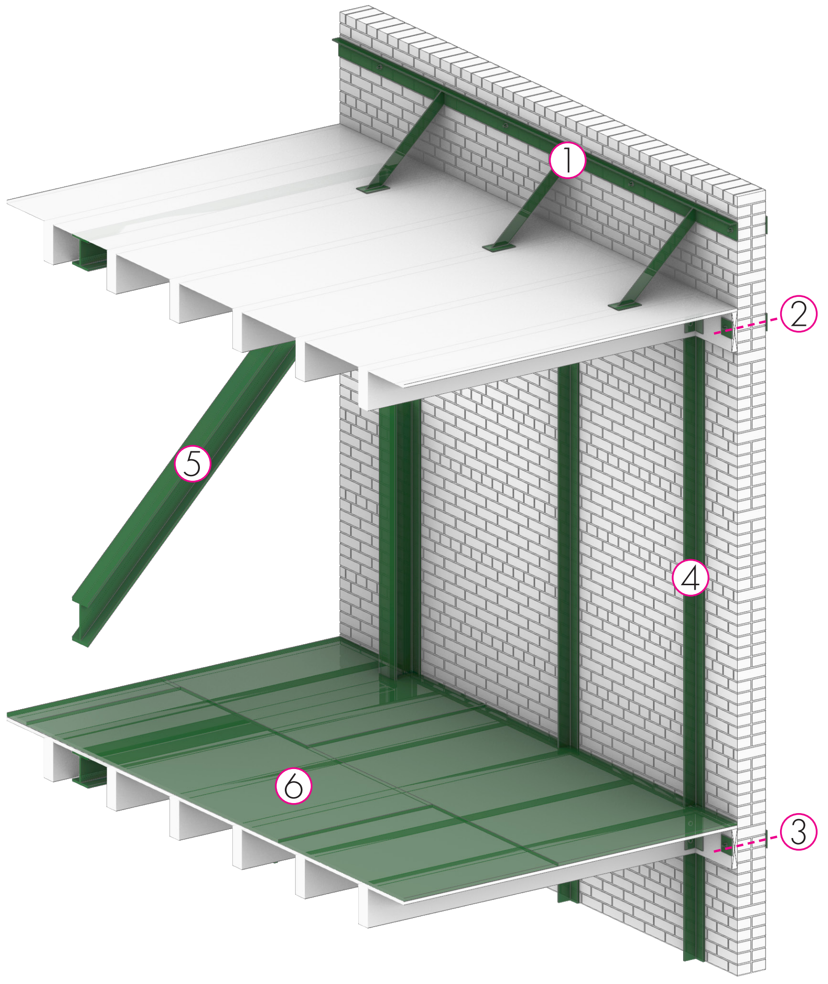


Figure 2.7 *Brick production in the Seattle area, illustrating the major decline in production during the 20th century despite continued population growth. (Adapted from Gurcke, Karl. 1987. Bricks and Brickmaking: A Handbook for Historical Archaeology. University of Idaho Press.)*



① PARAPET BRACING
Exterior wall extending past the roof line requires steel diagonal bracing

② WALL-TO-ROOF DIAPHRAGM ANCHORS
Exterior brick envelope is horizontally secured to the roof framing

③ WALL-TO-FLOOR DIAPHRAGM ANCHORS
Exterior brick envelope is horizontally secured to each individual level of floor framing

④ OUT-OF-PLANE WALL BRACING
Vertical steel columns mounted against the interior of the brick envelope to counteract bending forces

⑤ OVERALL BUILDING BRACING
Vertical and diagonal steel columns improve the overall strength of the building

⑥ DIAPHRAGM STRENGTHENING
Additional sheets of plywood sheathing fastened to the floors to improve strength

Figure 2.8 *Types of seismic retrofits for improving the safety, strength and longevity of unreinforced masonry buildings. (Adapted from Redding, Stephanie. "Seismically Retrofitting URMs." August 10, 2015. Digital Illustration. Seattle Times. https://www.seattle.gov/emergency-management/hazards/unreinforced-masonry-buildings-%28urm%29-)*

from the site in the 1950's with the construction of I-5. Their manufacturing facility moved to Newcastle, with clay extracted from nearby Cougar Mountain. The site's distinctive red clay produced many well known buildings in Seattle, including the pavers and buildings around Red Square on the University of Washington campus (Figure 0.3). Mutual Materials recently ceased operations at their Newcastle site, but they maintain a steady presence in the Pacific Northwest with twelve manufacturing facilities and two mining sites still in operation.

Seismic Concerns and Preservation Opportunities

The Pacific Northwest coast is a seismically active region, resulting in regular earthquakes of varying strengths that have collectively had a major impact on the past and future outlook of the local brick industry. Seattle is in a particularly precarious position, as the Cascadia fault line runs directly through the city (Figure 2.9). A series of earthquakes in the 20th century exposed the vulnerability of local unreinforced masonry structures during these natural disasters. The largest Richter scale measurements occured in 1872 (7.3), 1949 (7.1), 1965 (6.5) and the 2001 Nisqually earthquake (6.8). The Nisqually earthquake caused over $1 billion dollars in damages to buildings and infrastructure, including many aging brick buildings (Figure 2.10).

The most vulnerable brick structures during an earthquake are referred to as unreinforced masonry buildings (URM's). These buildings were generally built before code changes in 1945, and are composed of an envelope of multi-wythe brick walls that serve as both the primary structural element and the exterior rain screen. During an earthquake, the exterior walls are susceptible to separating from the interior floor systems and collapsing. The parapets of these structures are also at risk of breaking away from the main structure during the back and forth shaking movements of an earthquake.

There are more than 1,100 URM structures in Seattle, and only 15-20% of them have the necessary structural retrofits required to be able to withstand seismic damage (SDCI 2024, Figure 1.8) Fortunately there are a number of prescribed retrofits that can help improve these aging structures, primarily by reinforcing the connection between the brick envelope

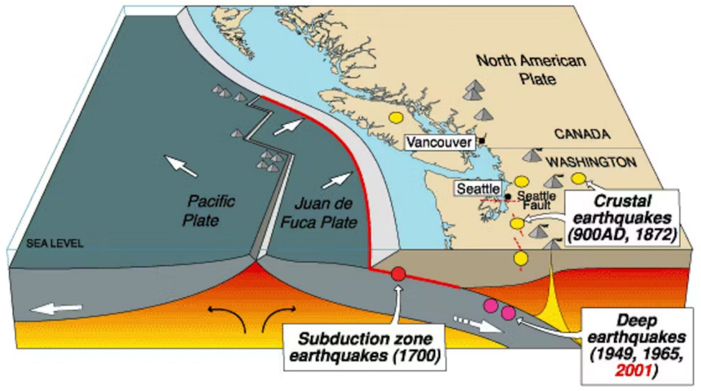


Figure 2.9 *Illustration of the Cascadia subduction zone and fault lines running through the Seattle region, posing a risk to residents and buildings (USGS)*

and parapets to the interior structure (Figure 2.7). But these can be expensive repairs that the owners of these older buildings may not be able to afford. Considering the risk that the structures pose to public safety, the city of Seattle has been preparing legislation that would make these retrofits mandatory for building owners to provide. But due to the aforementioned expense of this work, the result could be an increase in demolitions rather than preservation projects.

While public safety should be prioritized above all other factors, numerous environmental and socio-economic reasons exist for preserving these historic masonry structures. First, there is a high level of embodied carbon in masonry buildings due to the amount of energy required to vitrify the bricks during their production. In addition to the embodied carbon, there was a significant amount of environmental damage that occurred in the procurement of the clay to produce the bricks. Preserving these buildings allows the bricks they contain to have a longer lifespan and a higher return on the initial investment of energy and environmental cost associated with them. Second, the preservation of these aging buildings retains the unique aesthetic character of these neighborhoods to survive and to celebrate the high level of craftsmanship they exude. And finally, these aging buildings typically offer cheaper rents to both business owners and residents than can be offered by newer structures with significantly higher costs of construction that drive up rent prices. As Jane Jacobs noted in her highly influential book The Death and Life of Great American Cities, "new ideas require old buildings" (Jacobs 1961). In order to maintain vibrant and diverse neighborhoods that celebrate the creativity of new business owners and residents, aging structures must be preserved to house those people and ideas.

Recognizing these potential benefits, the city of Seattle and local organizations like the Alliance for Safety, Affordability Preservation (ASAP) are advocating for additional funding sources to support property owners. Federal grants from FEMA are a possibility, and the city is considering a program that allows URM owners to sell unused development rights to fund retrofits. These sources are critical in determining a path forward that prioritizes public safety while also celebrating and preserving the history of Seattle's local brick industry.

Figure 2.10 *Damage to the Cadillac Hotel in Pioneer Square after the 2001 Nisqually Earthquake (Photo courtesy of Erik Stuhaug from the Seattle Municipal Archives)*

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Figure 3.1 *Clay mining with high pressure hoses in 1890's Renton, WA (Photo courtesy of Renton History Museum and Museum of History & Industry)*

Chapter 3

Clay Mining

This chapter presents an overview of the clay excavation process in order to illustrate some of the immediate environmental impacts of the brick industry. With baseline evidence of how these post-industrial landscapes have been impacted, plans for improving these sites can be more easily and effectively established.

As noted in the previous chapter, the abundance of clay across the planet is one of the main reasons for brick's prevalence across thousands of years of human construction. This abundance allowed for the excavation of clay and production of brick near the final location of a building site, as temporary kilns known as "clamps" were often constructed and dismantled alongside the period of construction (Campbell 2003). This early production often excavated only the necessary amount of clay required for local buildings, as shipping brick was slow and costly. But this resulted in less reliable brick quality due to the inconsistencies in soil types and kiln construction. As production increased during the mechanization of the Industrial Revolution, much larger amounts of clay were required to keep up with the demand. This increased production started to create larger scale and more permanent impacts on local landscapes that were being excavated. Improved transportation, particularly with the expansion of railways, allowed bricks to be shipped farther from manufacturing centers. As a result, brick producers could identify larger and higher quality clay deposits on the periphery of cities where they could focus their efforts as opposed to smaller sites closer to the city center. Large, heavy mechanized equipment allowed excavators to dig deeper and more efficiently through these expanding clay pits.

This increase in brick production came at the cost of more severe landscape degradation. Larger scale excavation in concentrated locations, as opposed to smaller and spread out mines, created deeper rifts in the flows of ecological systems. And unlike other mining or logging operations that are relegated to distant locations, the ubiquity of clay has resulted in mines located relatively close to city centers. As a result, abandoned clay mines that were once at the periphery of city boundaries in the late 1800's and early 1900's have today been swallowed by urban growth, putting them in direct proximity to adjacent residential neighborhoods. The steep slopes of these mined areas present risk to local residents, and the poor health of local soils offers limited opportunities for native plant life to reestablish.

3.1 CLAY TYPES

Characteristics of Clay

Clay is not a singular material with universal properties - it is a component of soil that has many different variations and properties depending on its geological history. It is generally defined by its particle size (<0.002mm) and by its moisture-related properties: highly plastic when wet and brittle when dry (Moreno-Maroto and Alonso-Azcárate 2018). Clay is composed of fine-grained phyllosilicate minerals that impart characteristics of plasticity. These minerals derive from a parent rock material that has been exposed to and transported by erosive forces. The type of clay in a region is dependent upon site specific environmental factors such as parent material, climate, topography, vegetation, and the length of time that those factors have operated on the clay minerals (Reeves, Sims, and Cripps 2006). There are four main methods of clay deposit formation: residual clays are formed in situ by high temperatures and high rainfall environments, hydrothermal clays via volcanic activity, transported clays by the movement of surface water over weathered topography, and glacial clays from ice sheets grinding subsurface parent material into smaller clay sized particles.

Among worldwide minerals, clay is the 8th most excavated material and the 19th most valuable (Reeves, Sims, and Cripps 2006). 90% of excavated clay material worldwide is used for structural applications, such as bricks, roof tiles, and pipes (ibid). Of these structural uses, common clays/shales and refractory clay are the most frequently used clay types.

Per their name, common clays and shales are the most frequently found materials and are typically used for large scale production of bricks (Glover 1941). These clays are often located near the surface of the earth or exposed along ravines and river edges. They are not considered particularly high grade materials, and can contain impurities while still being suitable for brick production. Refractory clays, on the other hand, are more rare and valuable than common clays and shales. They are often formed by igneous rock parent material and can be found near areas of volcanic activity, but frequently at greater depths that require expensive mining operations to access. Refractory clays have a higher alumina content that allows them to withstand higher temperatures, making them valuable in industrial processes that require exposure to high heat.

Washington Clay Characteristics

In the Pacific Northwest, the majority of clays are glacial till deposits formed by the expansion and contraction of the Cordilleran ice sheet (Glover 1941). These clays are generally common clays and shales found near the surface of the earth. Volcanic activity along the Cascade mountain range also provided sources of hydrothermal clay deposits. These are typically associated with the refractory clays found near Mount Rainier and the deposits at the eastern end of the state. This is reflected in Figure 3.2 and 3.3, which show the distribution of common clay and refractory clay mines across Washington state and King County. While refractory clays were discovered in more isolated regions, common clays and shales are generally located adjacent to high population centers

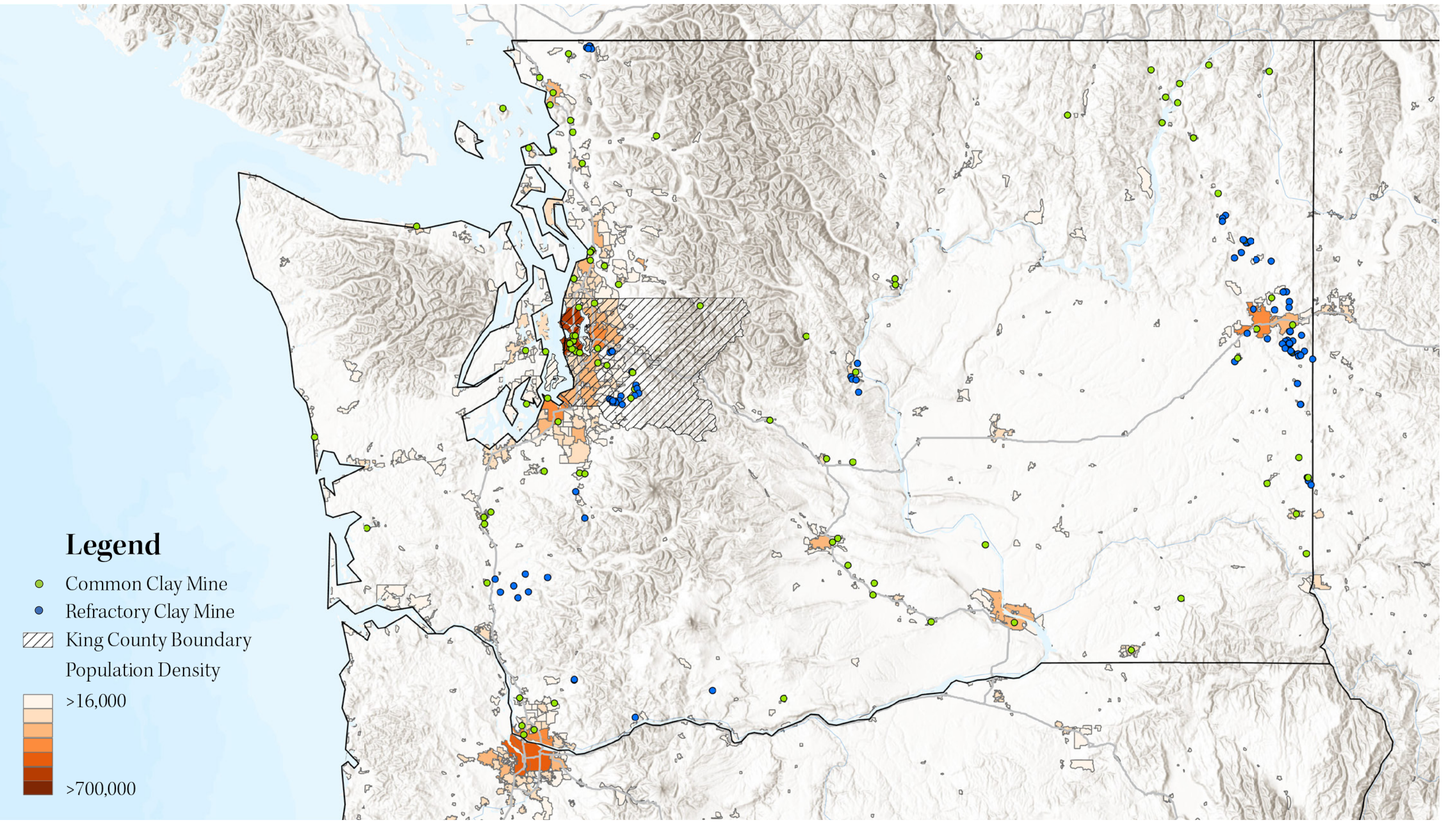


Figure 3.2 *Clay mines and population density in Washington State*

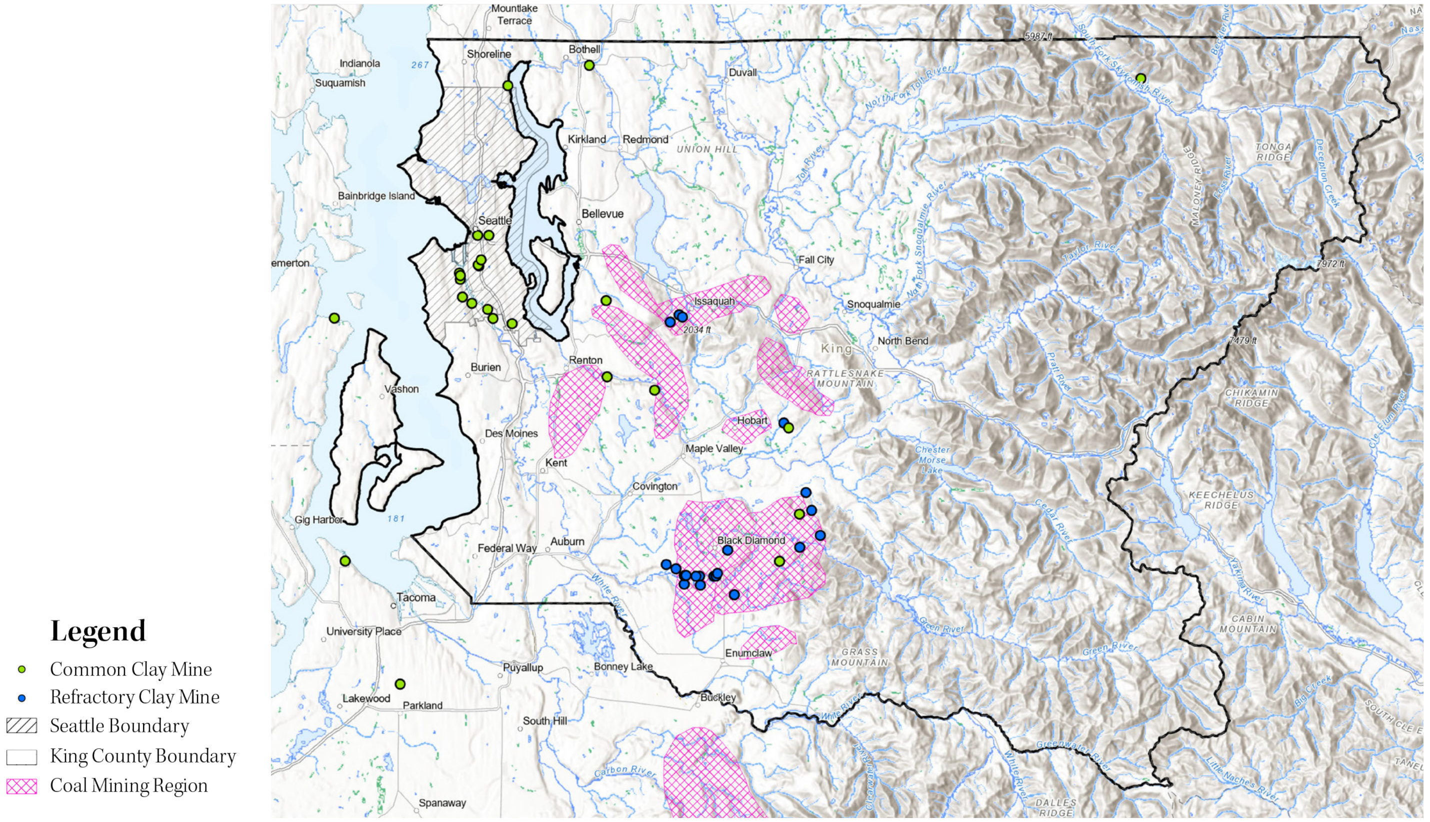


Figure 3.3 *Clay and coal mines in King County*

where they were used for construction purposes.

3.2 CLAY MINING

Prospecting Mine Locations

Clay is not always discovered via deliberate prospecting; historically it has been more commonly identified while excavating for another reason such as agriculture, mining or road construction (Glover 1941; Reeves, Sims, and Cripps 2006). This was particularly true prior to the modern use of remote sensing technology and advanced boring techniques. This is apparent in the arrangement of clay mines found near present day Seattle (Figure 3.3). Nearly all of the recorded refractory clay mines in King County are located within coal mining regions, where existing deep tunnel mining practices were exposing veins of the industrial clay material alongside the coal deposits. It was expensive and labor intensive work to reach such depths, so the only economically practical method for extracting these clays was while it was paired with another industry such as coal mining (Glover 1941). In addition, this paired industry supplied the energy required to fire the bricks.

Within the Seattle city limits, the arrangement of clay mines offers a different story that is reflective of the clay's immediate characteristics and eventual utilization. Analysis of clay mine maps reveals that much of the clay that helped rebuild Seattle in the late 1800's was mined along the Duwamish River valley, an area that is currently industrial infill but was once a winding river estuary flanked by steep edges of glacially carved bluffs (Figure 3.4). This location offered several benefits that are key components of clay excavation: close proximity to the final construction sites, adjacency to transportation routes, and favorable topography that facilitated excavation.

The proximity to the Duwamish river encapsulates all three of these advantages. The river provided an initial transportation route between the mines and downtown construction sites, as well as transportation for deliveries outside of Seattle. Eventually railroad lines would connect these sites and provide an

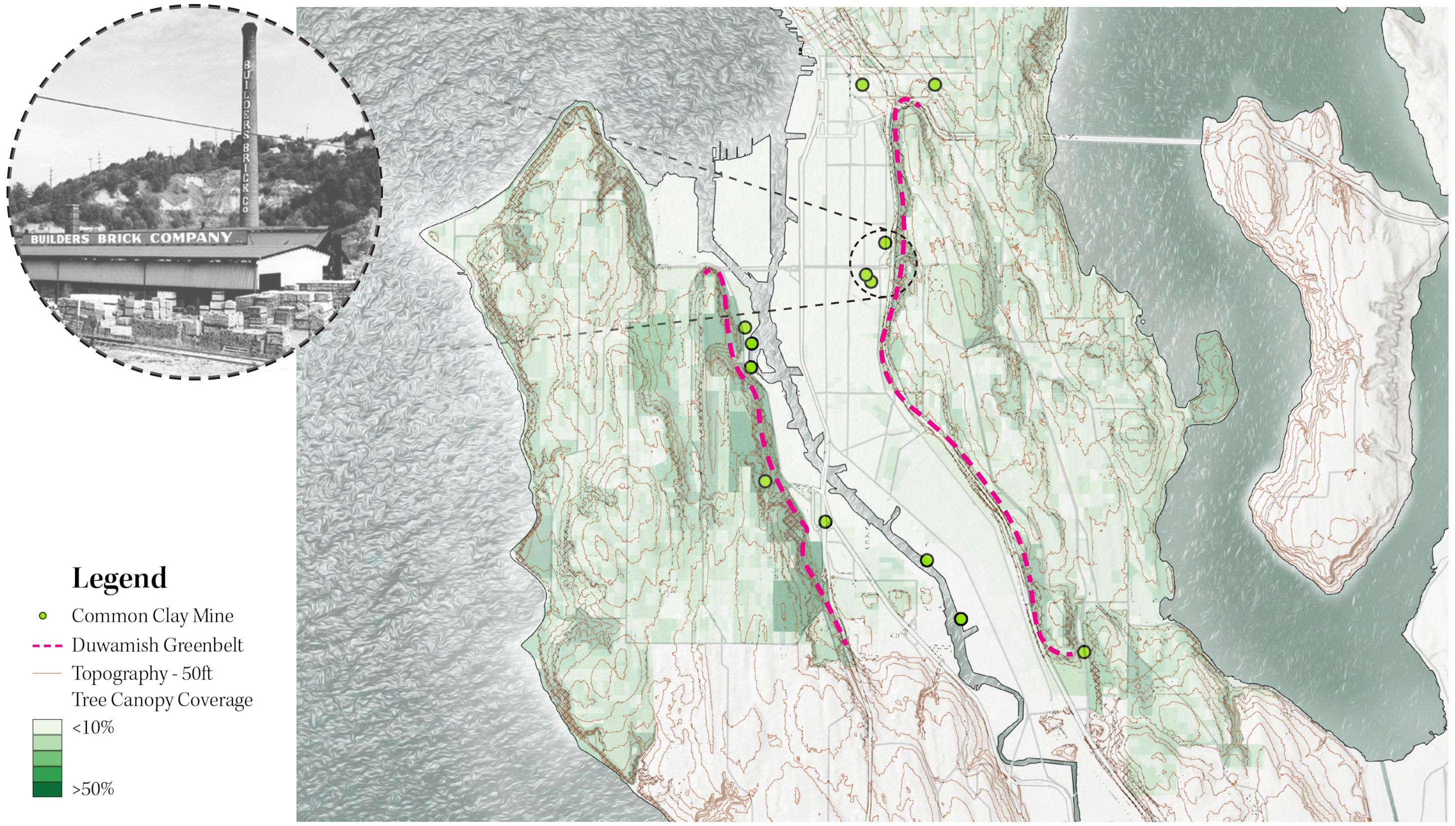


Figure 3.4 *Clay mines in South Seattle located along the East and West Duwamish Greenbelts, dividing what would otherwise be a continuous strip of undeveloped land with valuable ecosystem benefit potential.*

additional mode of transportation for such heavy cargo. Additionally, the river itself served as an ancient prospector by slowly carving away the glacially formed bluffs and visually exposing deposits of clay within the hills. This allowed early settlers to easily identify these stockpiles without advanced prospecting equipment. This hillside exposure also made the process of excavation easier, as detailed in the next section.

Production facilities were commonly built directly next to the clay source in order to limit transportation between the clay pit and the manufacturing equipment. The direct access to transportation routes also allowed large shipments of coal and other fuel sources to arrive at the factories and heat their large kilns. These businesses ran on very slim margins, relying on large scale orders and limited expenses in order to make a profit. Deciding on the final location of the plant could have a drastic effect on the company's fortunes (Glover 1941).

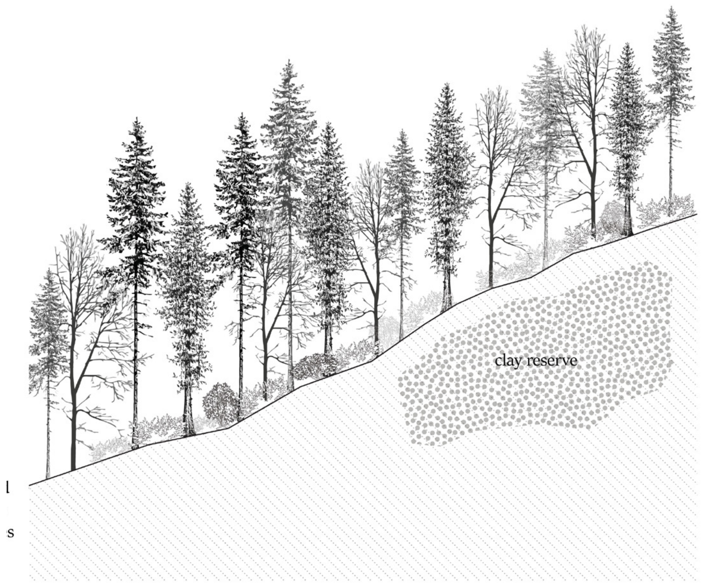


Figure 3.5.A *Pre-industrial conditions (Image by author)*

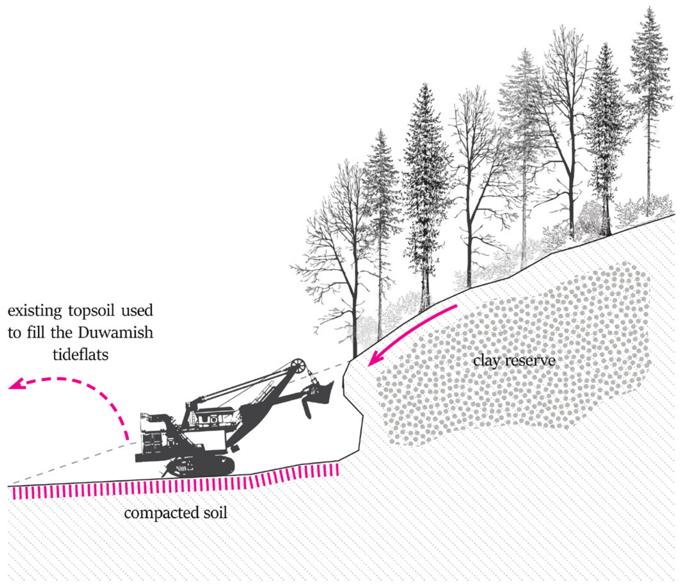


Figure 3.5.B *Late 19th - Early 20th Century Mining (Image by author)*

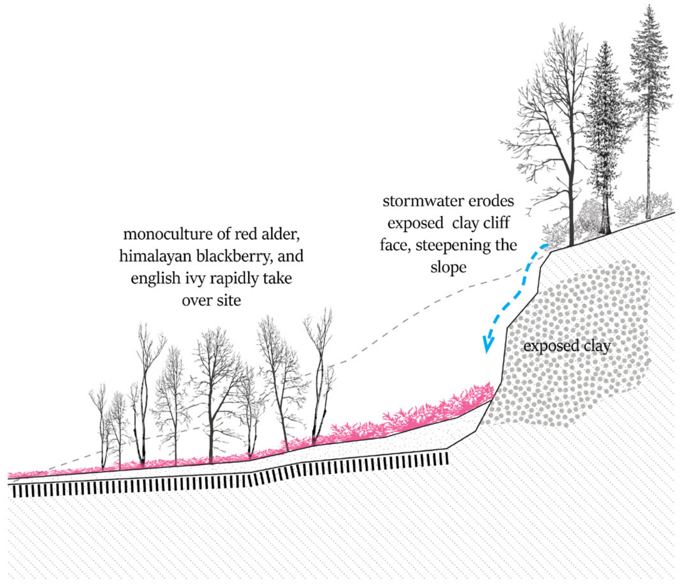


Figure 3.5.C *Post-Industrial Use (Image by author)*

Figure 3.6 *Present day conditions at the former clay mine site of Builder's Brick Company along the border between North Beacon Hill and SODO (Photo by author)*

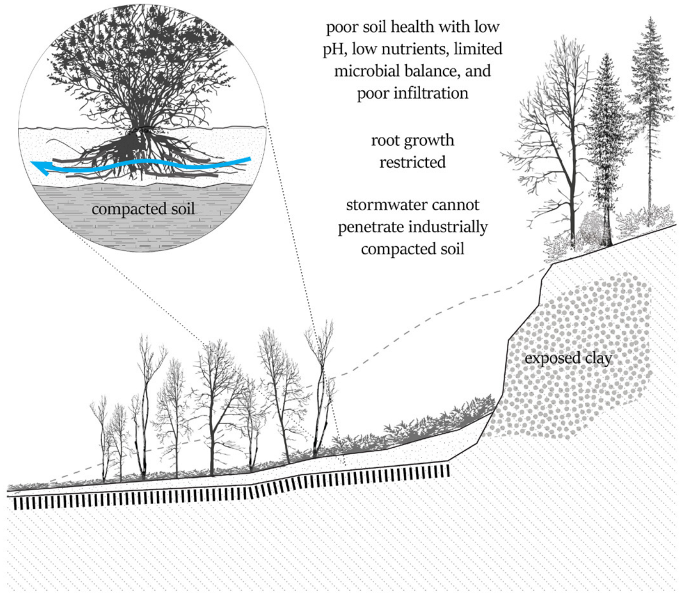


Figure 3.5.D *Compacted Soil (Image by author)*

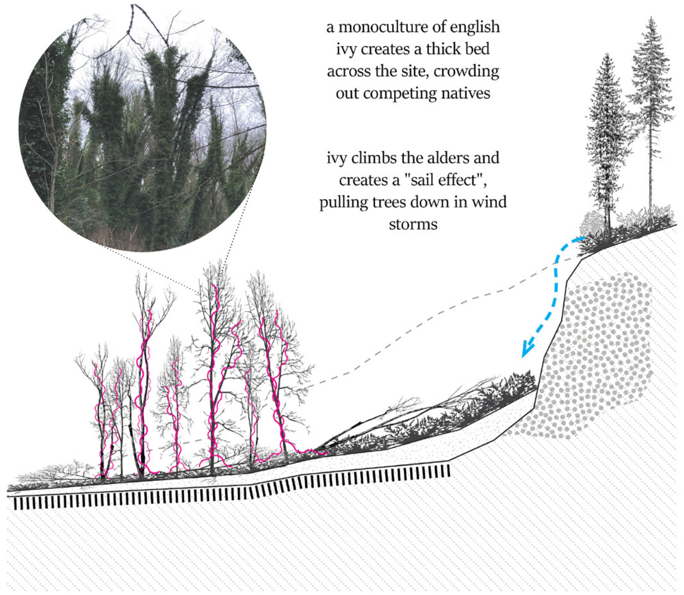


Figure 3.5.E *Present Day Invasive Plant Growth (Image by author)*

Clay Excavation Methods

Clay excavation in the Seattle region utilized four main methods of extracting clay (Glover 1941; Gurcke 1987; Shedd 1910). Undermining was the most commonly used process and took advantage of the steep topography along the Duwamish River valley. Large excavating machinery such as power shovels as well as explosives were required to undermine the foot of a hillside. This created an unstable base and took advantage of gravity to encourage upper soil strata to collapse downwards, revealing a bank of clay below. This exposed clay was then scraped away and sent directly to conveyor belts or truck beds for transport to the adjacent production facility, as illustrated in Figure 3.5.

Other methods included open pit mining, in which clay was exposed in "benches" of soil to reach vertically down to subsurface clay reserves. Hydraulic mining involved high pressure water that hosed down the topsoil and let it settle down to a pickup location (Figure 3.1). This was particularly prolific in the series of regrades that took place across the downtown area, and was also effective in these mining efforts . And finally, "glory hole" mining involved a deep vertical excavation that connected to a horizontal tunnel below where clay was vertically funneled into carts for transport. This was a particularly destructive method and was more common in the coal mining territories to the southeast of Seattle, such as the Taylor mining community.

Environmental Impacts

Topsoil stripped from the site contains the seed bank and natural soil organisms that kept the soil healthy and balanced. By removing this upper layer, all that is left are lower horizons of dirt. These lower levels offer far fewer nutrients and do not have adequate soil texture, density or acidity levels to sustain native plant life. In addition, these newly exposed layers are repeatedly driven over by heavy mechanized machinery, creating highly compacted "pan" layers of poor nutrient soil. (Cooke and Johnson 2002) (Zipper et al. 2013; Turrión et al. 2021)

The passage of the Surface Mining Control and Reclamation Act in 1977 required mining companies to restore the land they worked on. However, all work prior to the passage of this act is not held to the same standard and requires alternative means of intervention in order to be restored.

Case Study - East Beacon Hill Clay Mine

The impact of mining operations along the Duwamish River valley is most clearly demonstrated by an investigation of the former Builder's Brick Company mine. The site is southeast of the present day's I-5 - Columbian Way junction, a steeply sloped bluff separating I-5 and the industrial zone to the west, and the residential Beacon Hill neighborhood uphill to the east. The site was mined from 1900 through the late 1950's, when the construction of the highway forced it to relocate (Burkitt 1999). The mine provided clay for an adjacent brick manufacturing facility, which produced common brick, structural brick, and clay tile (Shedd 1910). The 2005 Geological Map of Seattle by USGS reveals that the lower soil deposits are composed of lacustrine deposits, the mid layers are Lawton clay, and the upper layers are advanced outwash deposits (Troost). The upper two layers were likely the most valuable for brick production, as they had higher clay contents and marked the transition from transported river sediment to more finely grained glacial deposits.

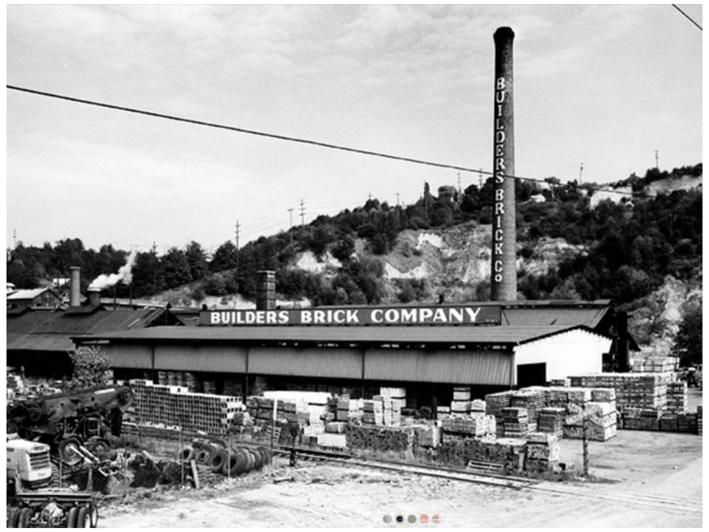
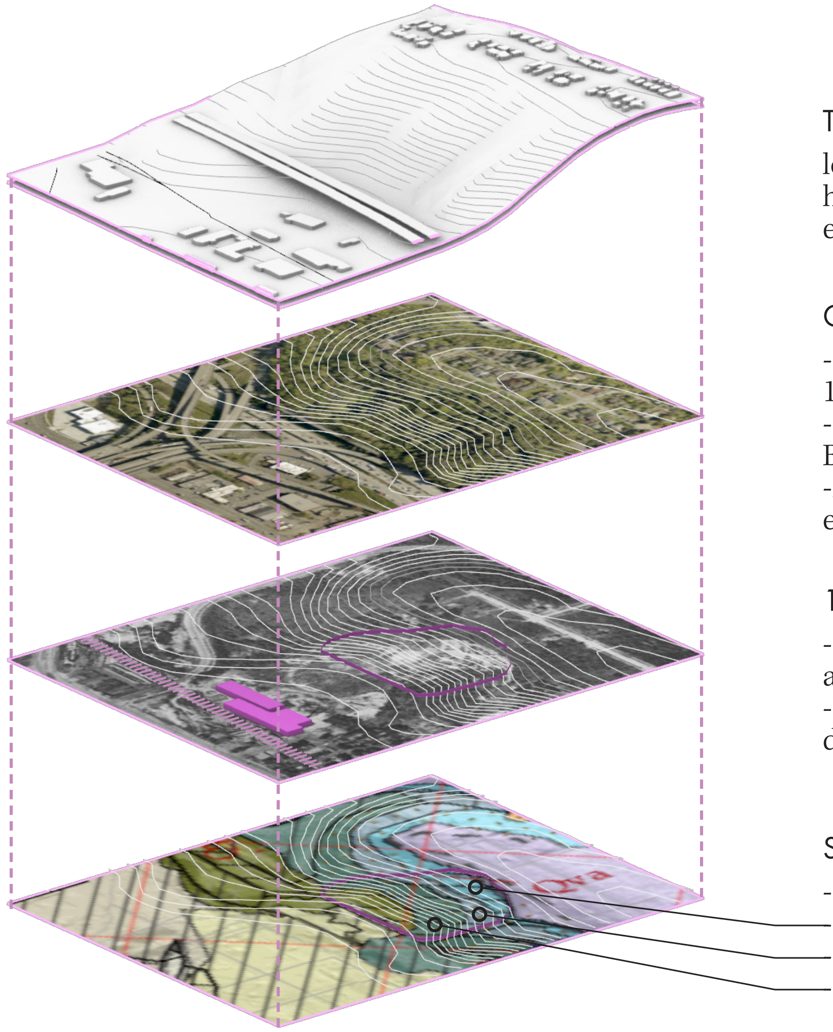


Figure 3.7 *The original Builder's Brick Company location at the base of Beacon Hill (Photo courtesy of Mutual Materials)*

Figure 3.8 *The Beacon Hill clay mine, operated by Builder's Brick Company until the construction of I-5 in the late 1950's (Photo courtesy of Solon Shedd)*



TOPOGRAPHY
low point: +20'
high point: +304'
elevation change: 284'

CURRENT CONDITION
-Brickmaking facility demolished in 1950's for the construction of I-5
-Clay pit is now part of the East Beacon Hill Greenbelt
-Mainly red alder and rampant english ivy groundcover

1936 CONDITION
-Brick manufacturing facility directly adjacent to clay mine
-Railroad west of facility and mine delivered material

SOIL CONDITIONS
-Blue glacial clay
-Qva: Advance outwash deposits
-Qvlc: Lawton clay
-Qpof: Possession lacustrine deposit

Figure 3.9 *Axonometric overlay of the underlying geological and social factors that have shaped the Beacon Hill clay mine (Image adapted from Troost et al. and King County GIS)*

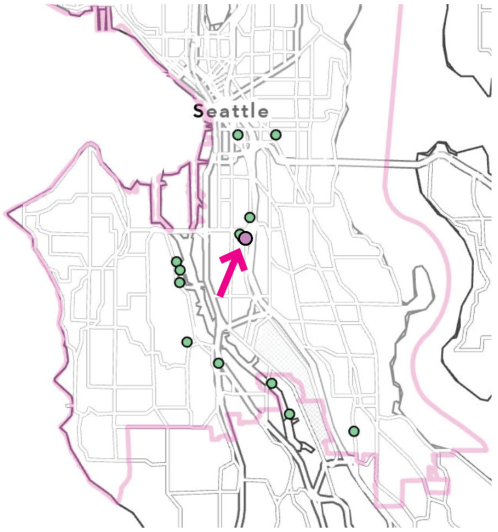


Figure 3.10 *Key plan highlighting Builder's Brick Company among other clay mines along the Duwamish River Valley in Seattle, WA*

The mined areas are clearly delineated by a transition in the topography of the site, an inward dip that resulted in a steeply faced edge. At this relatively early stage in American mining practice and before the passage of the 1977 Surface Mining Control and Reclamation Act, topsoil was likely not preserved for future use. Instead, it is likely that topsoil excavated to access the clay below was used as landfill for the growing industrial zone at the base of the bluff. A series of regrades in the area provided the earth to fill the former tide flat at the mouth of the Duwamish River, and additional topsoil from these mining operations was likely added to this large movement of earth (Hatfield et al. 2018).

This excavation transformed the natural hydrology and the ecological character of the site. During the open pit mining process, nutrient rich topsoil and all vegetation was removed, exposing underlying layers of earth that were continuously compacted by decades of machinery. This compaction led to a hard pan, not unlike the soils that result from repeated tilling in agricultural fields. Previously spongy soil that helped to soak up water was replaced by a less permeable medium that rapidly transported water across its surface. In the ensuing years plant growth has been limited to a monoculture of thick English Ivy and Red Alder, a tree known to thrive in recently impacted areas (Figure 3.5). The thick layer of ivy is climbing most of these trees and crowding out an opportunity for native species to take root in the nutrient poor soils that remain.

The steep slopes along the border of the clay mine have increased the landslide risk in the area, and continuous erosion of this exposed hillside has put the residential neighborhood to the east in a precarious position. It is evident that large portions of the hillside have slid away, and the city has resorted to slope stabilization and erosion mitigation interventions to prevent future erosion from tearing away the existing street (Figure 3.5.C). While the invasive English Ivy is preventing other plants from colonizing the area, its extensive root system is also likely responsible for preventing additional landslide activity.

Clay mining has created a zone in the heart of Seattle that is a hazard to humans and detrimental to ecological systems in the area. While these risks are evident, there is also great opportunity in this undisturbed natural buffer. The relative seclusion from the rest of the city has created a small wildlife refuge for birds and mammals in the area, as evidenced by a wildlife camera posted on site by the Seattle Urban Carnivore project. Coordinated efforts to improve biodiversity and address soil health via stabilization and nutrient balancing could lead towards a site that is healthy for humans, plants, soil and wildlife.

Figure 3.11 *Aerial photograph of present day conditions at the former site of the Beacon Hill Clay Mine. Steep surface erosion is visibly approaching the adjacent residential neighborhood (Aerial photo adapted from Google Maps)*

Figure 3.12 *Evidence of hillside erosion at the present day location of the Builders Brick clay pit is posing an increasing threat to adjacent residents (Photo by author)*

Figure 3.13 *English ivy climbing the branch of a downed alder at the site of the abandoned clay mine in Beacon Hill (Photo by author)*

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Figure 4.1 *Retired beehive kilns at the present-day Mutual Materials brick production facility in Mica, WA (Photo by author)*

Chapter 4

Brick Production, Construction & Demolition

While clay mining is responsible for site-based environmental degradation, the production and construction of brick has wider global impacts due to the material's high rate of carbon emissions that affects the entire planet. This section begins with a description of the brick production process, providing an understanding of how we arrived at our current manufacturing methods and identifying where improvements can be integrated into the process. It then shifts towards construction techniques involving mortar joints, which can increase or decrease the lifespan of the material independently of its production quality.

4.1 BRICK PRODUCTION

Brick Shaping Methods

One of the essential characteristics of brick is the standardization of module dimensions. Standard sizes make a material easier to transport, design, and assemble, while also improving opportunities for reuse after disassembly. Historically, manufacturing processes have been variations of assembly lines striving to create identically sized modules at high speeds with minimal waste material. To ensure identical dimensions, different types of handmade and machine operated devices were used to shape clay into bricks.

Today, there are three common methods for forming raw clay into its final dimensions: hand pressed, hydraulically pressed, and extrusion (Figure 4.2). Hand pressing, the first and oldest method, begins with a mound of wet, softened clay that is pressed by hand into a rectangular mold with parallel faces. After the clay is physically compressed in place, excess clay is scraped from the top of the mold. The filled mold is then flipped over to eject the formed clay brick so it can be laid out to dry. This method is slow and tedious compared to contemporary methods, and often results in varying quality due to the high amount of human error that can occur along with the wearing down of the mold over time. But it also does not require heavy machinery and offers the opportunity to construct bricks directly on the construction site rather than in a distant factory.

Hand Pressed
Soft-Mud (20-30% water content)

Machine Extruded
Stiff-Mud (10-15% water content)

Hydraulically Pressed
(<10% water content)

Figure 4.2 *3 primary brick production methods*

Th next method, hydraulically pressed brick, is the modern advancement of hand-pressed molding. It takes the same principle of shaping clay into the negative of a prefabricated mold, but with the added efficiency of modern machinery. Instead of hand-pressing brick, mechanized equipment compresses the clay substrate into the mold. This results in much more evenly distributed and controlled compression, while also considerably speeding up the process. Larger hydraulic presses can be permanently mounted to factory floors in larger operations, while smaller manually operated presses can be disassembled and reassembled more easily.

While the introduction of automated machinery results in an increase in brick production efficiency, there is also a level of assembly line uniformity that results in a different aesthetic from traditional hand-made bricks. Petersen Tegl is a brick manufacturer in Denmark that specializes in custom made bricks that match historic production methods to produce the hand-made aesthetic of historic buildings for architectural preservation projects. Hydraulic equipment presses clay into molds and ejects them with pressurized water. This creates a more randomly textured surface that can closely resemble the unique qualities of hand pressed brick.

The final shaping method, extrusion, is currently the most common in the United States, where about 90% of bricks are created using this process (Brick Industry Association 2006). The technique arose in the 19th century as the brick production process shifted towards automation (Campbell 2003). Instead of pressing material into individual molds, extrusion processes push clay through a brick-shaped profile into a long column of compressed clay (Gurcke 1987). The column moves along a conveyor belt before it is cut into individual brick units. This method is the most expedient, with the ability to create hundreds of thousands of bricks in a single day. It is also the least mobile, with the large and heavy machinery requiring the controlled environment of a warehouse. As a result, these large extrusion factories were placed as close as possible to clay reserves. As with other mechanically produced bricks, there is a level of uniformity to extruded bricks that can be lessened by adding more textural finishes during the extrusion and firing process.

Mutual Materials - Mica Plant

The last remaining brick production plant in Washington state is operated by Mutual Materials in Mica, a small city about 30 minutes southeast of Spokane along the eastern border of the state. This facility has been in place since the late 1800's, operating first under Gladding & Macbean, then Paccar, and today Mutual Materials (Waterbly 2023). The following is a walkthrough of their extruded production process, illustrating how harvested clay is transformed into brick through several main steps.

Figure 4.3 *Aerial photograph of Mutual Materials brick production facility in Mica, WA (Aerial photo courtesy of Mutual Materials)*

Step 1 - Raw Clay Storage

Clay is delivered to large covered storage areas at the manufacturing facility. Typically, it is transported from a clay mine located nearby, but some specialty clays is shipped in as well. Since clay can only be excavated during the dry months, manufacturers must have enough material on hand to be able to continually produce bricks throughout the year. Different types of product are stored in individual piles so they can be mixed as needed later on.

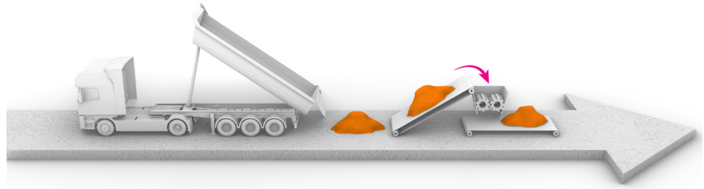


Figure 4.4 *Stockpiled clay (Photo by author)*

Step 2 - Preparing Clay Mixture

Harvested clay is gathered and mixed together in a large bin with a skid-steer loader. Different clays are incorporated to a mix based on performance characteristics and finish colors. A variety of particle sizes is desirable to create a stronger bond in the brick. Old or defective bricks crushed into smaller particles are also added. These pre-fired ceramic products are referred to as *grog*, providing valuable additives that improve the firing and drying properties of the brick (Waterbly 2023).

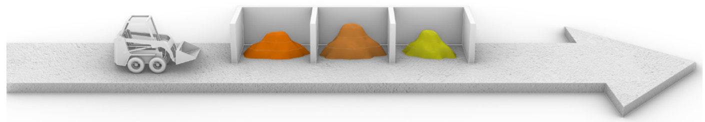
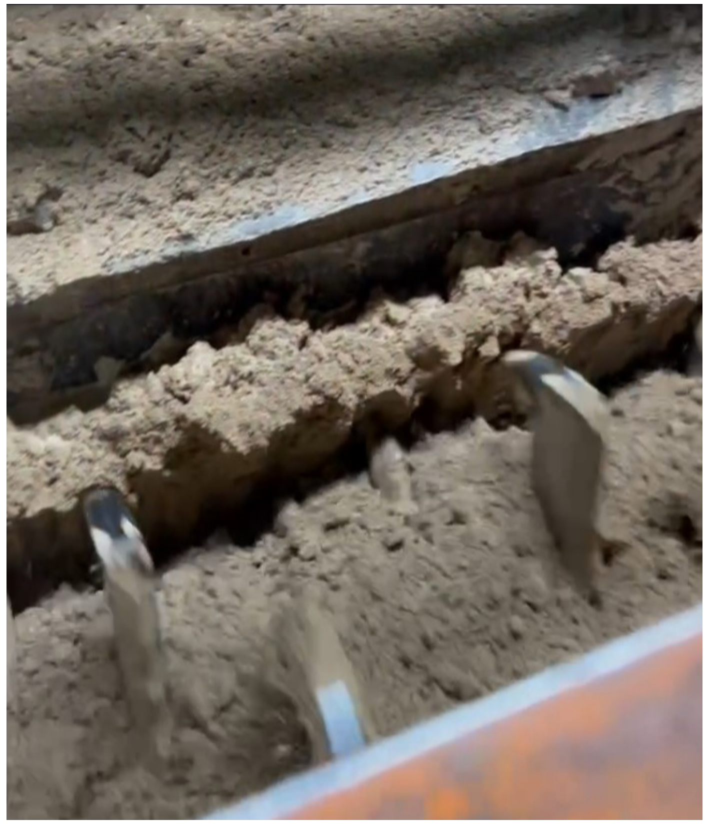


Figure 4.5 *Clay being mixed (Photo by author)*



Step 3 - Particle Size Reduction

The clay mixture along with castoff clay and recycled grog is delivered via conveyer belts to a series of rotating size reduction machines. This grinds the clay down to smaller and smaller particle sizes, after which they are sent through vibrating screens to ensure the maximum particle size is not exceeded. This mixture is sent to a rotating pug mill, pictured above, where water is also added. A water content between 10-15% produces the desired plasticity for extruded brick.

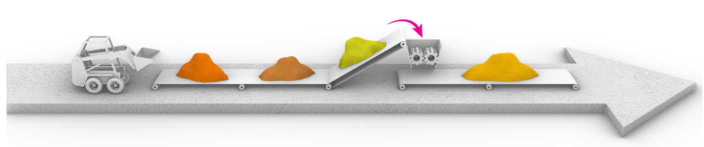


Figure 4.6 *Clay repeatedly ground down to remove larger fragments (Photo by author)*

Step 4 - Extrusion

Prior to extrusion, clay is sent through a de-airing chamber to remove air pockets and bubbles to increase the bricks' final performance. This prepared clay is then extruded through a small "die" profile that shapes a large column of clay into the desired dimensions. Inside the dye is a series of columnar rods that poke core holes into the clay to reduce their weight and improve mortar adhesion.

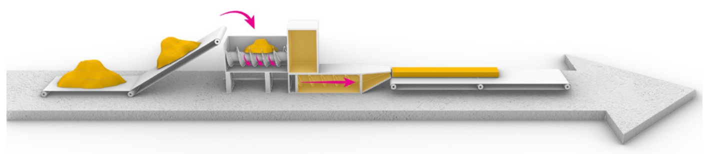


Figure 4.7 *Clay sent through extruder (Photo by author)*

Step 5 - Cutting

As the clay column exits the extruder, finishes can be applied via textured rollers on up to three sides of the brick, or other materials can be sprayed onto the column. The clay is then cut into individual units by a rotating wire cutter. The spacing of the wires can be adjusted to produce the desired brick dimensions. These dimensions must account for the eventual shrinkage of the clay that will occur in the drying and firing process.

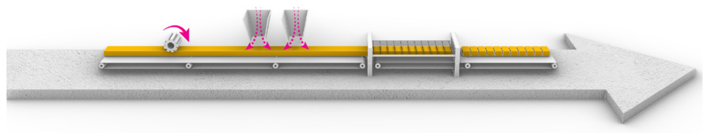


Figure 4.8 *Clay trimmed to individual units by a rotating wire cutter (Photo by author)*

Step 6 - Loading to Pallets

These final bricks are then stacked onto pallets before they are sent to the dryer. This is an automated process in most North American brick production facilities. However, the Mica plant still hand loads bricks onto pallets. This affords the flexibility to produce a number of specialty shapes from the die without having to calibrate expensive machinery, giving them more options from which consumers can select.

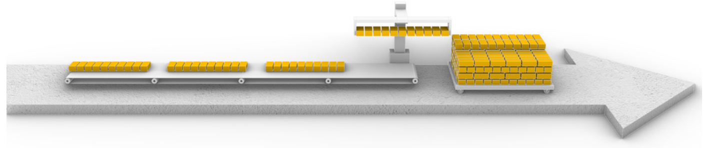


Figure 4.9 *Bricks transferred and stacked onto pallets (Photo by author)*

Step 7 - Drying

“Green” unfired bricks are stacked on wheeled pallet carts, then sent along tracks through an extended tunnel dryer. The carts are slowly pushed through the dryer for 1-3 days in temperatures between 38°C - 204°C. Much of the water contained in the bricks evaporates during the drying process. Heat in the tunnel dryers is provided from the exhaust emanating from the kilns and humidity is carefully controlled to limit cracking.

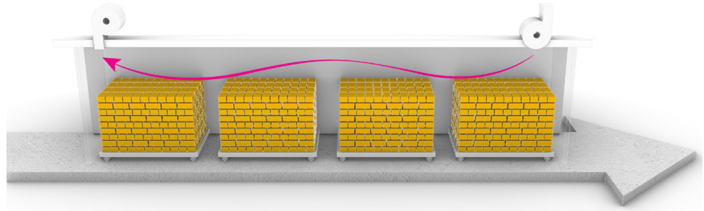
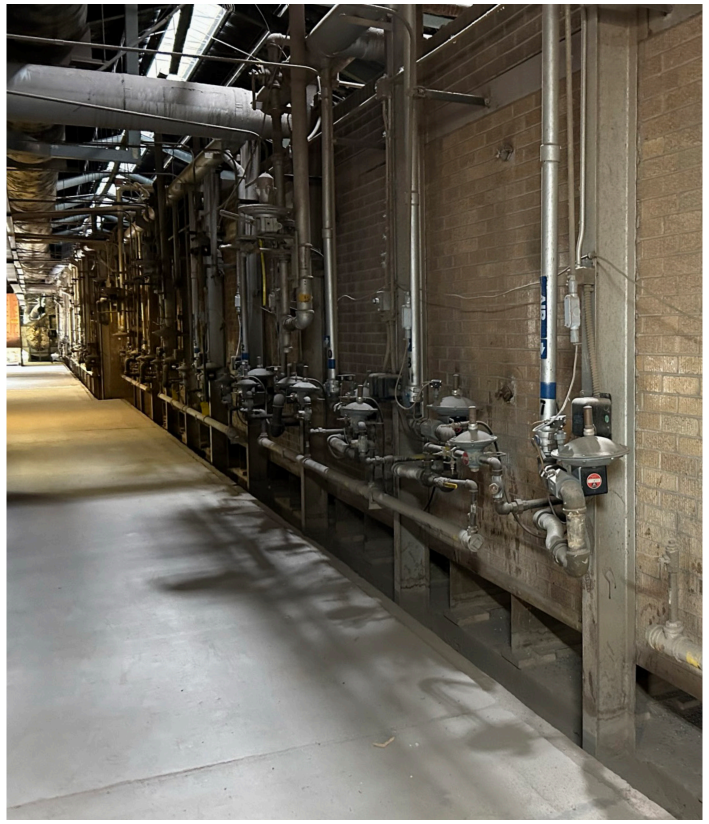


Figure 4.10 *Stacked pallets are sent to the dryer for 1-3 days (Photo by author)*



Step 8 - Firing

Dried brick pallets enter the tunnel kiln, a 400 ft long linear oven with natural gas heaters that carefully and continually regulate the temperature along designated intervals. Bricks begin the heating process at 150°C. As the pallets slowly travel along rails, the temperature gradually increases up to 1200°C as the bricks turn white hot and vitrify from the sustained heat, then slowly descend in temperature over 48 hours before they exit the kiln at room temperature.

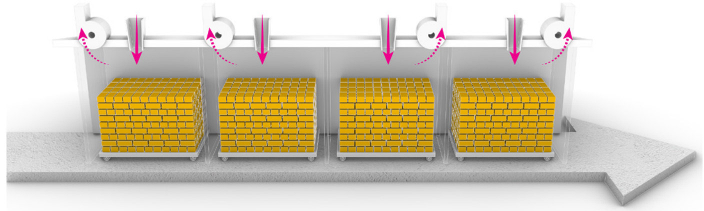


Figure 4.11 *Pallets continue to the tunnel kiln for 48 hours (Photo by author)*

Step 9 - Final Finishes

Upon exiting the tunnel kiln, bricks can be given final finishes in a cylindrical tumbler that simulates the aging worn edges of older bricks and provides variation between masonry units. Also, they can be sent to cutting machines which trim full size units into “thin-brick”. This brick is typically set in mortar or grout rather than as a traditional stacked wall element.

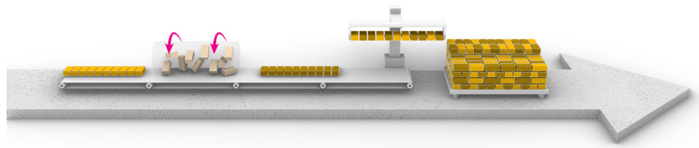


Figure 4.12 *Bricks inspected by hand, final finishes applied, and/or trimmed to thin-brick dimensions (Photo by author)*

Step 10 - Preparing for Shipping

Finished bricks are again hand-loaded from carts to their final shipping pallets. The Mica plant is located close to a train yard, where most of their material is shipped away. Due to their light-colored clays and their unique ability to make specialty shapes, their product is shipped across the continent and even internationally. This is a major departure from the history of brick, which was traditionally a more regionally specific material.

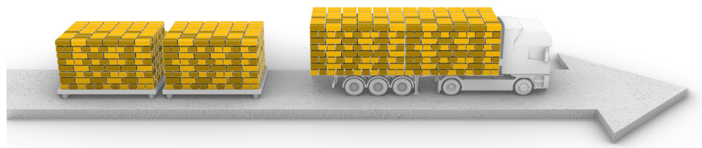


Figure 4.13 *Bricks stacked onto pallets and prepared for shipping via truck or rail (Photo by author)*

Areas for Improved Production

As illustrated above, the production of brick accounts for the extensive extraction of virgin clay material and a massive amount of energy for heating the kilns. But within each of these weaknesses are opportunities for major improvement.

Brick production does not necessarily require raw clay reserves. It instead can include a variety of other materials, including old bricks. There is an accepted value in adding *grog* - defective and crushed bricks - into the final clay mixture as it reduces dry times and improves firing performance in the kiln. The Mica plant in Washington has an abundance of grog due to their relatively poor clays which are more porous and less strong, resulting in a 15% rate of defective bricks that become available as grog (Figure 4.16). But many other facilities, particularly those on the East Coast of the United States, have defective rates as low as 3% and are therefore in need of more pre-fired and crushed ceramic material to add as grog to their clay mixes (Waterbly 2023). Incorporating higher amounts of waste materials in new brick production can limit the extent of landscape degradation due to clay extraction while simultaneously diverting waste from landfills.

The energy required to fire clay bricks is immense, requiring massive kilns to sustain temperatures up to 1200 degrees C for 365 days a year (Waterbly 2023). Unsurprisingly, the manufacturing process of clay fired bricks accounts for the highest carbon emissions impact within the full life cycle of the material (Figure 4.14). In order to make meaningful reductions in the embodied energy and potentially the cost of a brick, there need to be drastic improvements within this stage of the production process.

In addition to the carbon impacts of fossil fuel based heat, there is a major economic risk in being tied to the volatile energy market that has the potential to drive the cost of brick skyward. With the price of fossil fuel only expected to increase over time, the financial bottom line of brick is also tied to this finite energy source. By pursuing alternative energy sources or production methods, the industry could potentially also limit the cost of the material and improve its market viability in the future.

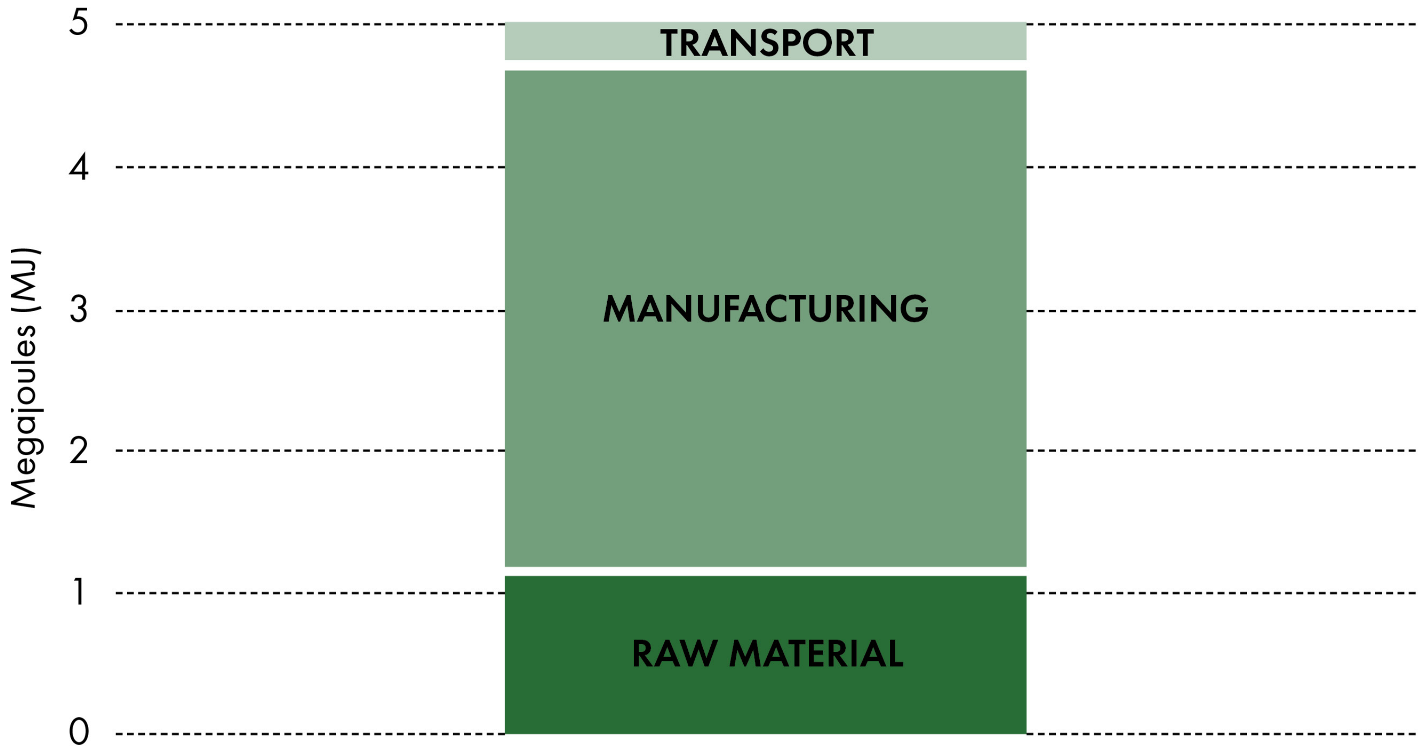


Figure 4.14 *BEES Life Cycle of Brick and Mortar "Energy Consumption Life Cycle Stage." Adapted from Hodge et al. "Quantifying potential benefit from material recycling." 2010.*

4.2 BRICK CONSTRUCTION METHODS

While the production phase of bricks impacts the embedded energy of the material, the construction method that connects each individual brick together into a built structure is the variable that often determines the operable lifespan of the material. Chapter 2 discussed the evolution of brick wall construction, illustrating the many different ways of assembling a wall. But each of these unique methods relied on mortar to connect individual bricks into a monolithic structure. This mortar is the key to brick's success in the past, but alterations that have led to our contemporary use of the material represent its weakness.

Mortar is the material that allows the adaptable and durable characteristics of brick to shine. In a traditional stretcher bond pattern, mortar accounts for 17.5% of the elevation (Brick Development Association 2023). While the mass production of brick invariably results in subtle irregularities, the mortar provides an initially soft cushion that infills these imperfections into a weather resistant whole. The curing of mortar creates a hardened and strong connection between the units. But the mortar must always be softer than the brick itself in order to allow inevitable cracking to occur along the joints. These joints can later be repaired in a process called tuckpointing, removing a thin outer layer of mortar and replacing it with new material. While this can be invasive and costly in the short term, it is more cost effective than replacing the bricks and only needs to occur every 30 years depending on the site and material conditions ("How Long Tuckpointing Lasts: A Guide for Brick Homeowners").

An informal poll during the assembly of this thesis revealed that people were aesthetically drawn towards old brick buildings, but disliked contemporary masonry structures. These new buildings were viewed as more rigid, sterile, and less susceptible to the comforting patina displayed by their older cousins. This current distaste for brick can be substantially attributed to the cement based mortars that have been commonplace in the United States since the 1940's.

Hydraulic Lime Mortar

Historically, mortar has been primarily composed of lime, gypsum, or mud mixed with sand and other additives (Brick Industry Association 2020; Brick Development Association 2023). Lime established itself as the primary mortar in North America as the European colonization of the continent brought their practices to new buildings. Lime based mortars are produced by heating limestone to 800 degrees C, transforming the fossilized algae in the stone into quicklime. The resulting powdery substance becomes volatile when exposed to water, and through the process of carbonization it releases CO2 and cures into a hardened, durable material. Combining this material with angular sand provides bricklayers with a reliable mixture for binding individual masonry units together.

The relative "softness" of hydraulic lime mortar provides a porous and easily workable material when compared to cement based mortars. The porosity of cured hydraulic lime mortar allows liquid and water vapor to wick through the wall, creating the necessary conditions for drying. It also allows for subtle movement in walls as a building settles over its lifetime, thereby reducing cracking in bricks (Jensen 2024). And at the end of a building's lifespan, the softness of the mortar allows for bricks to be individually disassembled and repurposed. Cast off hydraulic lime mortar can also be gathered, reheated and repurposed again as mortar in future applications. The characteristics of lime-based mortars allow brick to take advantage of its inherent advantages that align with circular economic models of design.

Portland Cement Mortar

The first recorded use of cement occurred during the Roman empire, when engineers added pozzolanic aggregates - volcanic ash - to create a stronger setting material. This technology was lost with the fall of the Roman empire, but re-emerged in early 19th century England when Joseph Aspdin patented Portland cement (Campbell 2003).

Cement is created by heating a combination of crushed limestone and clay up to 1500 degrees C before it is cooled and then further ground down into a fine powder. Lime based mortars, in comparison, are heated to 800 degrees C (Falkenburg and Mutterlose 2022). This difference in heating temperature accounts for the higher embodied energy in cement.

Joseph Aspdin's invention of Portland cement in early 19th century England and its widespread adoption in 20th century mortar mixes dramatically altered the makeup and characteristics of brick masonry. On the one hand, the use of cement in mortar mixes improved the strength of the material and drastically reduced setting times. This led to increased building efficiencies and lower costs that undoubtedly made brick construction more popular. The increased strength is also an asset when masonry wall construction shifted to single wythe veneer assemblies, which don't have the lateral strength of multi-wythe masonry walls (Nordby et al. 2009).

However, the onset of cement mortars also presented several disadvantages. The increased strength of the cement-based mortars exceeded the strength of the brick and limited the pliability of structures, leading to a higher risk of cracking and spalling. As a result, contemporary brick walls must use unsightly expansion joints in order to respond to movement and settling. Cement mortars are also less porous, leading to moisture issues in wall cavities or spalling due to water freezing and thawing within bricks. This requires additional previously unnecessary eyesore measures in wall construction to make up for the lack of porosity in contemporary brick walls.

On an aesthetic rather than performance level, cement based mortar lacks the attractive qualities of its historic counterpart. The lower firing temperature of lime mortars allows the crystals within the material to still "breathe" and self-heal over time as it reabsorbs carbon that was expelled during the initial carbonization process of curing (Falkenburg and Mutterlose 2022). This creates a certain "liveliness" that provides a polychromatic and textured character to the mortar (Jensen 2023). When the crushed up limestone in cement is superheated to temperatures above 1500 degrees C, the crystalline structures within the fossilized algae of the limestone collapse, and the material's ability to self-repair is lost. The result is a mortar joint that is relatively dull blue-grey and does not handsomely display its age as well as a lime based mortar.

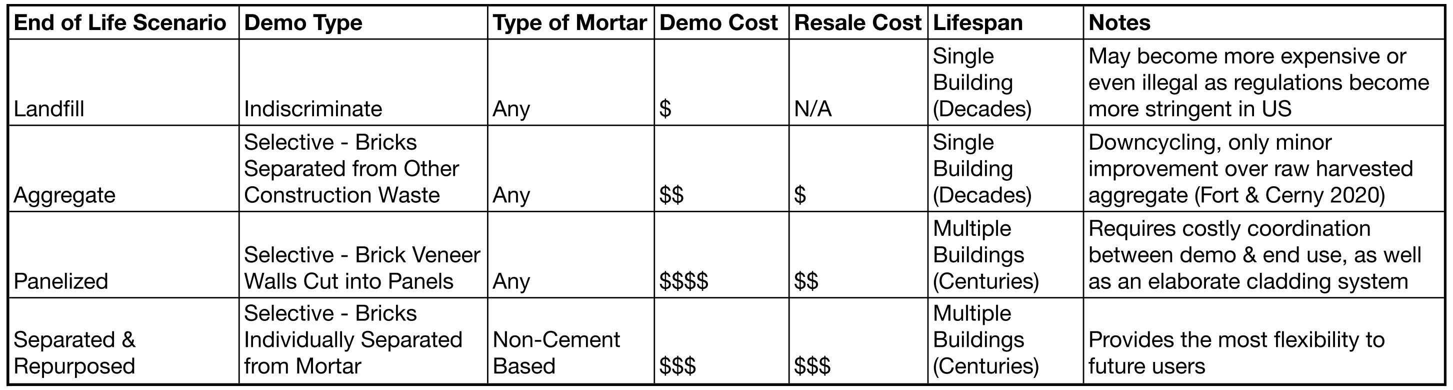
Perhaps the most drastic negative impact of cement mortars is its limitation on the long-term repurposing potential of individual brick units. The increased strength of cement mortars led to permanently bound walls with no economically feasible method of recycling them at the end of a building's operable lifespan. This limits the operable lifespan of a brick to the lifespan of a building, losing the potential for that brick to be used in a second or third life. In effect, this cuts the overall carbon efficiency of the individual brick by 50% or more, depending on the number of lifecycles it could have been used in (Figure 1.6).

4.3 BRICK DISASSEMBLY / DEMOLITION

The accelerated life cycles of contemporary buildings require owners to make decisions about the disposal of demolished construction components more frequently. Repurposed brick has proven to be a valuable commodity within the construction industry, as illustrated by their relatively high levels of reuse in Scandinavia. They can also be valuable resources for building owners to sell back to material suppliers at the end of a structure's lifespan. The patina that naturally develops on aging bricks is often a desirable trait for designers and owners, who can pay a premium for these authentic finishes. These profits can be used to offset the additional costs associated with selective demolition.

Although brick has a potential lifespan that spans centuries, the reality is that all brick buildings will degrade over time due to environmental exposure, regressive maintenance, or the changing needs of the property owners. As noted previously, the average lifespan for a brick building in North America is just 77.5 years (O'Connor 2004). The operable lifespan of bricks themselves have actually increased compared to historic alternatives, as our production processes have been refined to create a more consistent material. This indicates that the more lightweight interior structure of our contemporary buildings are failing faster than previously, or that the rapidly changing needs of property owners are prioritizing demolition and replacement over preservation or adaptation. At the end of a building's life cycle, property owners have to choose from four end of life scenarios for the brick material in their structures (Figure 4.15).

First, masonry buildings can be fully demolished with no attempt to preserve, gather or sort any of the brick units for reuse. All of the demolished materials are delivered to a landfill and permanently discarded as waste. This requires the least amount of labor, but the increasing cost to dispose of construction waste as well as legislative pressure is making it a less feasible option for property owners.



End of Life Scenario	Demo Type	Type of Mortar	Demo Cost	Resale Cost	Lifespan	Notes
Landfill	Indiscriminate	Any	$	N/A	Single Building (Decades)	May become more expensive or even illegal as regulations become more stringent in US
Aggregate	Selective - Bricks Separated from Other Construction Waste	Any	$$	$	Single Building (Decades)	Downcycling, only minor improvement over raw harvested aggregate (Fort & Cerny 2020)
Panelized	Selective - Brick Veneer Walls Cut into Panels	Any	$$$$	$$	Multiple Buildings (Centuries)	Requires costly coordination between demo & end use, as well as an elaborate cladding system
Separated & Repurposed	Selective - Bricks Individually Separated from Mortar	Non-Cement Based	$$$	$$$	Multiple Buildings (Centuries)	Provides the most flexibility to future users

Figure 4.15 *4 primary end-of-life scenarios for bricks.*
(Adapted from "ASTM C270: Standard Specification for Mortar for Unit Masonry." 2010.)

Second, demolished buildings can selectively gather waste bricks and send them to recycling centers to be crushed down into an aggregate. This aggregate is primarily used as subbase material in new road surfaces. While this is better than sending the material to a landfill, it is considered downcycling as it is erasing the high utility value built into the flexibly dimensioned brick. Also, crushing bricks and cement mortar requires a large amount of energy that further limits its circular potential.

The third scenario relies upon the careful deconstruction and disassembly of a masonry building into individual brick units. Traditional lime mortars used prior to the introduction of Portland cement are relatively weak and easy to disassemble. This process can be sped up further by incorporating the vibrational rasping techniques employed by Gamle Mursten in Denmark (see Chapter 7). Cement-based mortars utilized in more contemporary buildings make this process unfeasible, as it is too labor intensive to remove the adhered mortar without damaging the bricks. However, experiments that thermally separate the materials indicates another path for cement-based mortar masonry, but at the cost of the additional energy required to reheat the bricks and mortar (Braam 2020).

The final option at the end of brick's lifespan is to cut existing cement-bound brick walls into panels, which can be reused in their bound form on other projects. This is a highly labor intensive process that needs additional material inputs to produce a suitable backing wall for the brick panels. Despite these difficulties, the Danish firm Lendager Architects has proven this to be a net carbon improvement in the project Resource Rows, discussed further in Chapter 7. This strategy provides a potential path forward for the many cement-bound brick walls that make up the existing masonry building stock in the United States.

Figure 4.16 *Piles of bricks and masonry gathered from demolition sites at the Mutual Material's brick production facility in Mica, WA (Photo by author)*

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Figure 5.1 *Waste brick washed ashore at Nybøl Nor, a bay in the southeast corner of Jutland that is renowned for its high quality clays and the number of brick manufacturers that developed around its coast. Exposure to the elements eventually wears the bricks down until they are indistinguishable from naturally occurring stones (Photo by author)*

Chapter 5

Reconsidering Brick Life Cycles

The previous chapters have detailed each cycle within the lifespan of brick, identifying areas between production and demolition that require improvement in order to become a more sustainable material. But for brick to evolve into a material that fits within a Circular Economic (CE) framework, it is necessary to take a wider perspective that explores all of these cycles within a Life Cycle Analysis (LCA). This chapter explores the concept of circularity in the built environment, visually connects the dots between life cycle phases of the brick industry, and proposes an alternative CE framework for the brick industry via a series of coordinated improvements to each life cycle phase of the material.

5.1 CIRCULAR DESIGN & LIFE CYCLE ANALYSIS

The rising interest in sustainable design strategies in the construction industry has led to the present day push towards “circularity” in design thinking. There is no single definition of circular design, but it is instead referred to as the opposite of the current Linear Economy (LE) and its “take-make-waste” philosophy (Saidani et al. 2017, Figure 5.2). The result of the current materially wasteful system is illustrated in Figure 5.3’s visualization of the human made anthropogenic mass outnumbering the global biomass on the planet (Visual Capitalist 2020). This startling graphic puts into perspective how rampant our resource consumption has become, particularly within the built environment. To combat this trend, CE strategies focus on individual resource flows and their impacts on the social, economic and environmental spheres of society (Guldager Jensen and Sommer 2018). In the construction industry, CE design considers how one can limit the amount of natural resources being extracted by repurposing waste inputs towards the production of new materials. LCA tools are utilized for researching the impacts that materials have on humans and the environment, standardized through the issuance of Environmental Product Declarations (EPD).

There have been a variety of conceptual sustainable frameworks since the mid-20th century, but their primary focus centered on limiting energy consumption in the operational phase of the building’s life cycle (Amory 2019; Guldager Jensen and Sommer 2018). CE design strategies instead thinks beyond the operational phase of building materials, aiming to address all chapters of a material’s life cycle, from initial extraction to eventual disposal.

CE works at a variety of scales, ranging from the macro (countries and cities), meso (industrial parks, college campuses), micro (single companies, individual consumers) and nano (buildings, materials) (Amory 2019). When considering the nano environment that buildings inhabit, CE is further simplified into two realms: circular material selection and circular design.

The first type, circular material selection, focuses on the specification of materials that utilize renewable resources which have limited environmental and health impacts. In the brick industry, this correlates with the type of material the brick is composed of, and the type of energy inputs required to create it. Material selection in the traditional brick production method would specify raw harvested clay and fossil fuels to heat the ovens that fire clay bricks, while a more circular method would be to use renewable alternatives to clay and alternative production methods to firing. The second type, circular design strategies, focuses on products that are designed for disassembly, allowing them to last through

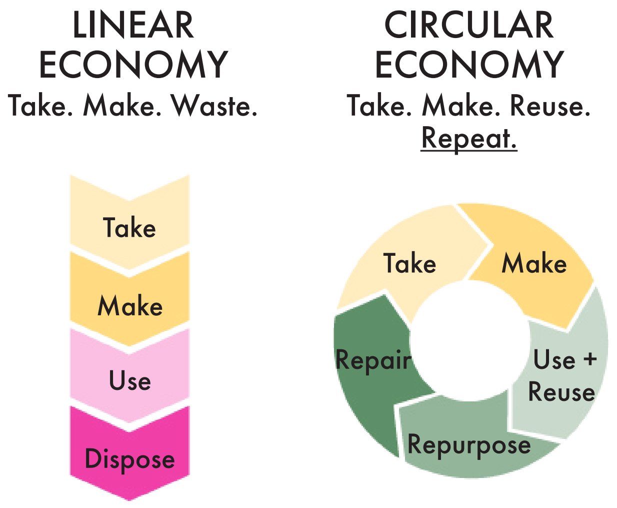

Figure 5.2 *Illustration comparing material use in a linear and economic model (Diagram by author)*

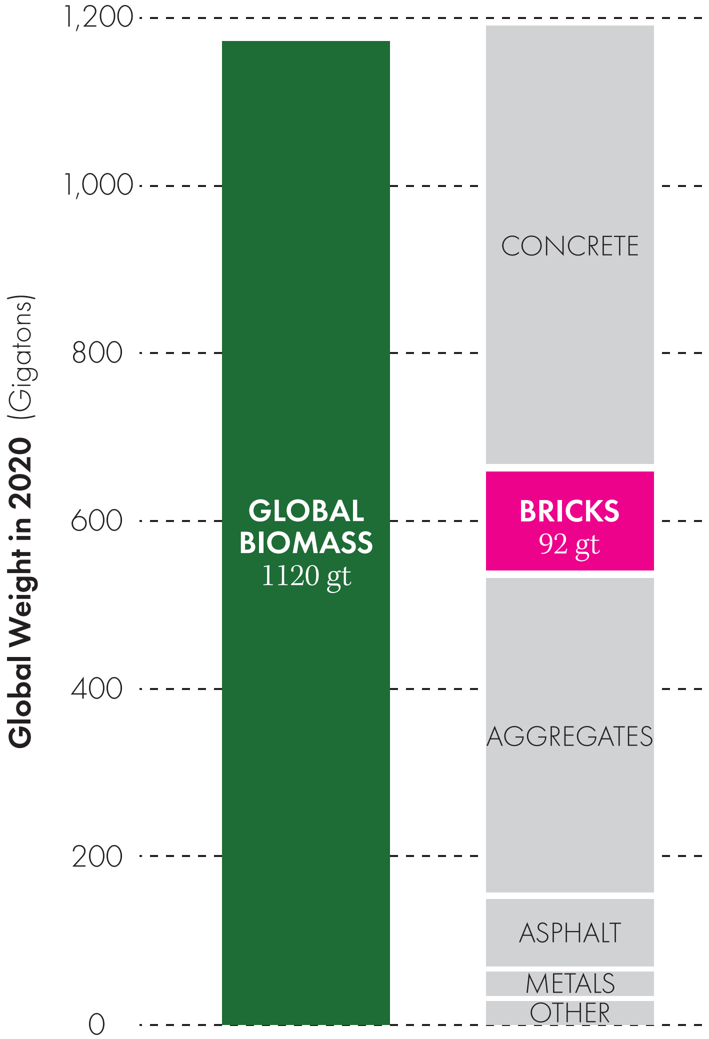

Figure 5.3 *Illustration visualizing the weight of man-made anthropogenic mass, which has now exceeded the weight of global biomass (Adapted from 2020 graphic by the Visual Capitalists)*

multiple life cycles of utilization. In traditional brick construction, this relates to the mortar that fastens each unit together. In a circular system, it is necessary to specify mortars that provide adequate strength for the durability of the structure but also allow for eventual disassembly.

The following LCA exercise explores revisions to the nano scale of the brick industry, incorporating targeted alterations to the material selection and construction strategies that can make it compatible with CE principles. Case studies of commercially available examples of these approaches will be further explored in Chapters 6 and 7. These strategies are then simultaneously implemented in Chapter 8.

5.2 TRADITIONAL BRICK LIFE CYCLE

An overview of present day brick's life cycle is visualized in Figure 5.4, highlighting areas that must be addressed in order to maximize the positive circular characteristics of the material. Some of these negative characteristics are inherent to bricks from all time periods, such as the high embodied energy expended during the firing process. Others have developed more recently as construction technology has changed, such as its limited capacity for reuse due to cement mortar. Both these inherent and developed traits require improvement in order for brick to evolve into a more sustainable building material.

5.3 IMPROVED BRICK LIFE CYCLE

By making a series of targeted adjustments along this life cycle, it becomes apparent how brick can evolve from a nostalgic to a circular material (Figure 5.5). The individual changes noted here can make a meaningful contribution to sustainable design, but their combined impact is exponentially more powerful as its newfound adaptability allows low-carbon materials to embrace their durability across multiple life cycles of buildings. For example, a lime-based mortar on its own will allow bricks to be reused, but it would still be reliant upon a high energy production cycle. In the same vein, a brick composed entirely of construction and demolition (C&D) waste will still be limited to a single building life cycle if it is constructed with permanently binding cement-based mortar. But by combining these traits, the adaptability reinforces the durability, and vice-versa.

The first step is replacing the ecological impacts of clay harvesting with redirected construction waste in order to provide a low-carbon alternative that can be produced with locally harvested debris and reduce waste being sent to landfills. Much like solar panels can become net-positive when they send excess power back to the shared grid, brick can behave similarly as a carbon-bank sequestering and extending the embodied energy within C&D debris.

Second, alternatives to traditional kiln-based firing can make the most significant reduction to the embodied energy in each brick. Binding materials could be used that permanently form C&D waste into brick molds. But the impact of these binding materials needs to be accounted for within the life cycle analysis of the brick to confirm they have acceptable environmental impacts and do not overly limit the durable potential of traditional fired-clay.

Third, distribution distances can be reduced by creating more production facilities closer to urban centers. As brick production became more efficient in the 20th century, the number of facilities shrunk and were consolidated into larger facilities. Due to the rapid expansion of transportation routes and logistic technology, these facilities were located further from city centers where the majority of

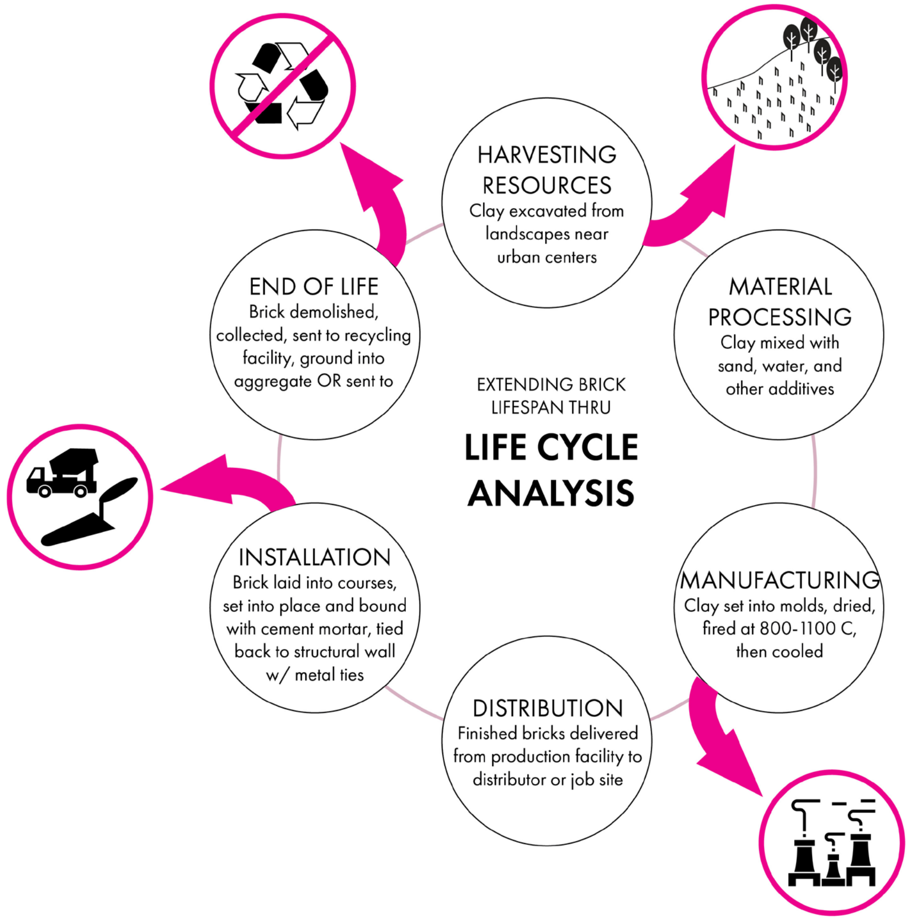

Figure 5.4 *Traditional brick life cycle (Diagram by author)*

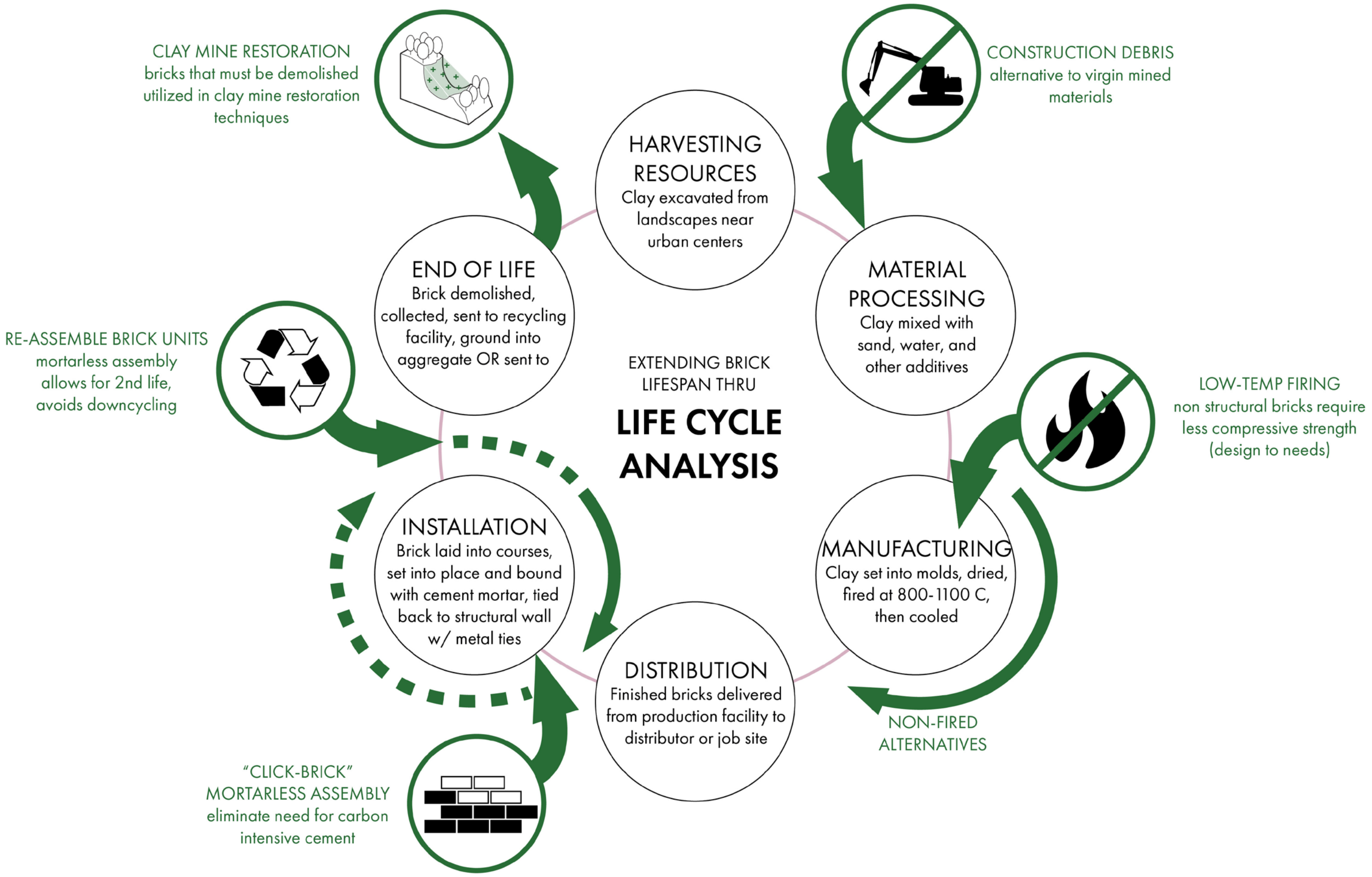

Figure 5.5 *Improved brick life cycle (Diagram by author)*

building construction occurs. This further increased the embedded energy of the material due to the distance they are shipped from their production site. By shifting from clay to C&D waste as the primary brick substrate, cities become regenerative producers of the materials used to construct themselves. And by linking production centers to local C&D waste centers, they can be produced in closer proximity to their final construction site.

Next, brick construction methods that transition from permanently binding cement mortars to traditional lime mortar or mechanical fasteners could encourage disassembly at the end of a building's lifespan. This allows the durable nature of brick to take full advantage of its centuries long lifespan by dramatically simplifying the disassembly and reuse potential across multiple building life cycles.

And finally, eventual end of life scenarios for brick can consider sending bricks back to their original excavation point to help with the ecological restoration of clay mines. A case study analyzed in Chapter 6 reveals a potential use for used bricks as a stormwater filtration system on a retired clay mine site. Chapter 8 further considers how demolished bricks can be used both as filtration and as slope stabilization materials in a former clay mine within Seattle's city limits.

The strategies that are visualized in Figure 5.5 represent the great potential that brick has within a CE, and particularly how individual efforts can be magnified if they are integrated in tandem. Many of these techniques are returning to the original vernacular origins of brick production (Dabaieh, Maguid, and El-Mahdy 2022). The following chapters indicate how these interventions can restore bricks inherent sustainable attributes while also continuing to develop it into a contemporary building material suited to address the environmental crisis of the 21st century.

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Figure 6.1 *Volunteer group planting Spirea douglasii around the perimeter of a constructed wetland on the site of a former clay mine on Cougar Mountain in Renton, WA (Photo courtesy of Heidi Rose Watters)*

Chapter 6

Case Studies - Clay Mine Restoration

This chapter provides references for best management practices for the restoration of clay mines in urban locations. It begins with a brief review of ecological restoration considerations and a general roadmap for the recovery of abandoned mine sites. This is followed by a series of case studies that investigate the post-industrial treatment of clay mines from a range of historical scales.

6.1 ECOLOGICAL RESTORATION STRATEGIES

Ecological restoration can be defined as "The reestablishment of the capability of the land to capture and retain fundamental resources" (Cooke and Johnson 2002). Chapter 3 illustrated the specific impacts of clay mining, in which local geology and ecology had been impacted so severely that it lost its ability to "capture and retain" due to plant removal and soil degradation. While the mining activities that altered these sites are singular events and relatively simple to trace, their restoration involves a wide-ranging series of interventions that are more successfully defined by the process as opposed to a predetermined outcome.

There are several site based factors that can have a dramatic impact on those processes. The first of these is whether the topsoil was stockpiled for reuse on site, or if it has been removed and made unrecoverable (Cooke and Johnson 2002). There is tremendous value in maintaining the existing topsoil and redistributing the minerals and hydrological properties it contains back across the site. A site without this topsoil is severely hampered due to the remaining substrate's lack of necessary nutrients, particularly N, P and K. Expectations for recovery should be amended to account for a lack of nutrient availability.

Most modern mining sites in the United States are required to maintain existing topsoil through the legislative requirements of the 1977 Surface Mining Control and Reclamation Act (SMRCA), which states that "the surface configuration achieved by backfilling and grading of a mined area should closely resemble the general surface configuration of the land prior to mining, and should blend into, and complement, the drainage pattern of the surrounding terrain" (Martín Duque et al. 2021). This necessitates planning ahead for the staging of existing topsoil material for later redistribution. However, mines prior to 1977 did not have to follow this requirement and often would send their topsoil elsewhere. In the case of the Duwamish Valley clay mines, the topsoil was very likely used as landfill in the massive regrading project that transformed the former river tideflats into flat industrial land in the early 20th century (Hatfield et al. 2018).

Another major consideration is whether the primary use of the site will be geared towards human or wildlife users. This is often determined by the location of the clay mine and its proximity to adjacent populations. In the case of Seattle's urban clay mines, well considered methods of restoration have the potential to imbue significant social impacts on the adjacent populations. This is in contrast to clay mines in more isolated locations, where restoration will be more focused on restoring ecological function with relatively limited interaction with human visitors (Turrión et al. 2021). An equitable approach that satisfies both ecological and human needs is a challenging balancing act between the divergent user groups, and will have distinct impacts on later decisions.

Academic research stresses the importance of maintaining an agreed upon process with well defined goals for various intervals of time (Cooke and Johnson 2002; Martín Duque et al. 2021; Turrión et al. 2021; "Stewardship Planning Guide" 2014). Each of these sources propose uniquely detailed guides for restoration, but their strategies can be summarized by long term and site specific interventions that consider Slope Stabilization, Soil Restoration, Plant Selection, and Continued Maintenance. Slope Stabilization limits the impacts of erosion in areas that have been stripped of their topsoil and are susceptible to further weathering. Soil Restoration improves the nutrient availability of substrates in order to promote future plant growth. Plant Selection considers which living material should be removed, kept, and/or introduced in order to promote a healthy and self-supporting ecosystem that compliments its surrounding context. And finally, Continued Maintenance creates a plan for regular human interventions to the site by providing necessary physical, economic and environmental resources over a designated period of time.

There is no "one size fits all" solution to these ecological restoration techniques due to the great variation of global ecologies impacted by mining. Instead, there are a variety of resources at a local, state and federal level that provide restoration information most relevant to a site. Chapter 8 will integrate this variety of guidelines along with concepts from the following case studies into a restoration strategy that is specific to the abandoned urban clay mines of Seattle.

6.2 CLAY MINE RESTORATION PROJECTS

Cougar Mountain - Mutual Materials

The restoration efforts at a former clay mine in Cougar Mountain Regional Wildland Park provide a useful reference due to its proximity to Seattle (15 miles southeast), exposure to human visitors, and similar ecological characteristics. The mine was operated by Mutual Materials, formerly Builders Brick Company, which shifted clay excavation operations from a former Beacon Hill mining site in the late 1950's when the construction of Interstate 5 forced them to relocate (Burkitt 1999). The mine provided raw materials for a nearby brick manufacturing facility in Newcastle that produced over 900 million bricks for many Seattle landmarks, including Safeco Field (now

T-Mobile stadium) and Red Square on the University of Washington campus (Burkitt 1999). It ceased operations in 2012 and the land was turned over to the King County Parks Department.

The former mine is in the center of a public wildland park interlaced with frequently visited hiking trails. Due to these paths and expansion of surrounding residential areas, the interface between the site and recreational visitors had to be considered by the parks department. In addition to the clay mining operations that occurred on site, there were also remnants of extensive coal mining operations in the surrounding park. Rather than erase this history with a full restoration to pre-mining conditions, the parks department chose to reference and maintain access to some of these industrial remnants. This is typified by the protected entrances to retired coal mining shafts and informative plaques that remain along several trails. A similar strategy was decided for the clay mine restoration, which recognized educational value in referencing the industrial heritage of the area and in preserving the view corridors to the Cascade mountain range that were created by the clearing of the treeline (Lund 2023). It also provides a more cost-effective strategy for a project with a limited budget.

Historic preservation considerations were balanced with efforts to reintroduce native plants while dealing with increased surface water runoff. The initial mining operations in the 1960's removed the topsoil from the site, creating an immediate setback for restoration efforts due to the remaining hardened soil that limits percolation, exacerbating stormwater issues and limiting planting success rates (Lund 2023; Cooke and Johnson 2002). For this reason, newly planted trees were focused along the edges of the site where there was additional topsoil depth available (Figure 6.3). The center of the site presented a hard pan of exposed and compacted clay soils. This area was gently graded to encourage a central flow along the hiking trail until it reached a new wetland area, providing a low point for surface runoff that is ringed by native wetland plant species (Figure 6.4).

Beyond this wetland area is a large pile of rejected

Figure 6.2 *Photo from the western entry to the former clay mine at Cougar Mountain. View is looking towards Tiger Mountain to the right and the Cascade Mountain range to the left (Photo by author)*

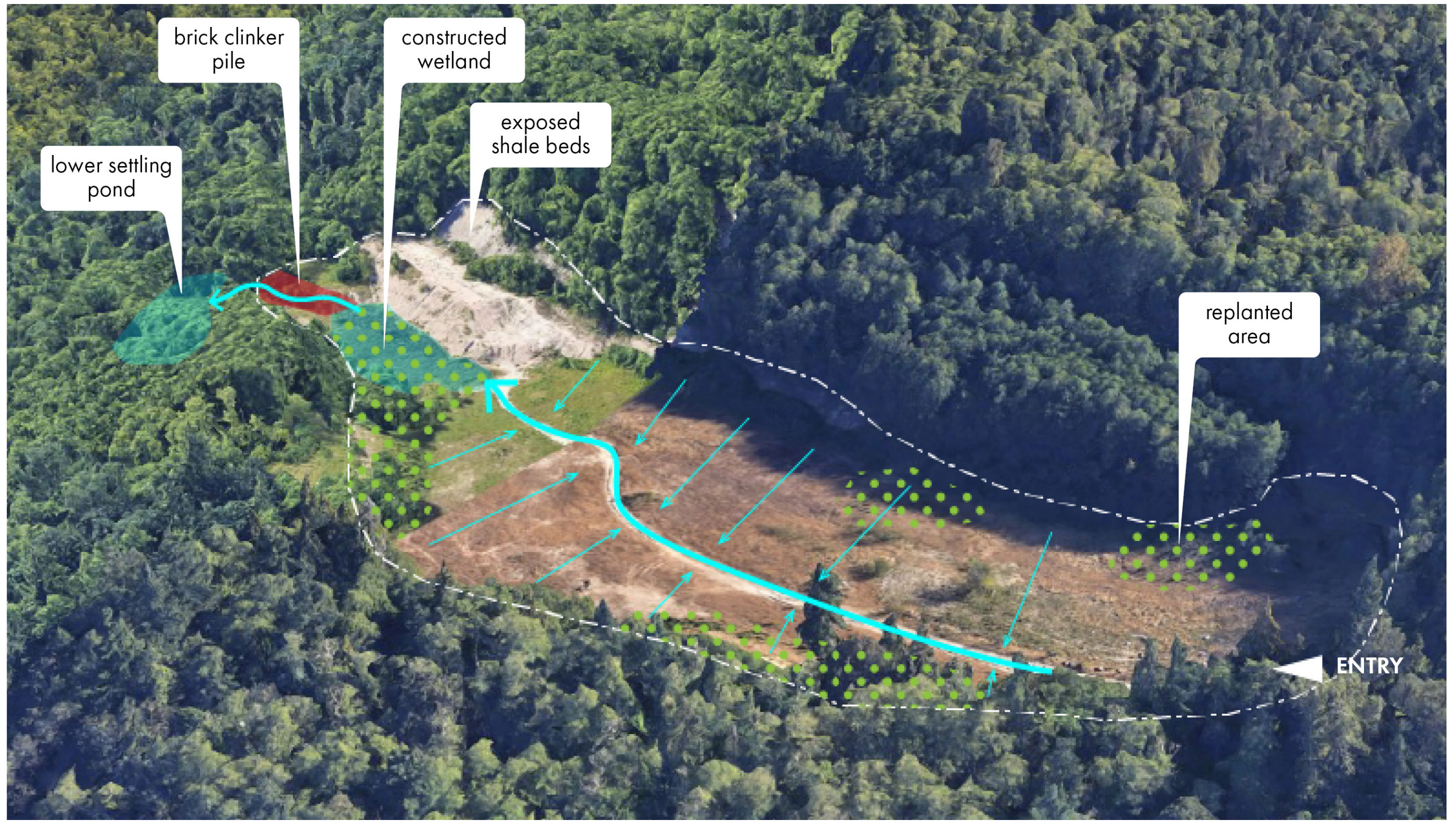

Figure 6.3 *Site plan of the restoration interventions orchestrated by the King County Parks Department and various volunteer groups (Aerial image adapted from Google Maps)*

Figure 6.4 *Stormwater surface runoff is guided down the central hiking path of the site. Remnants of industrial excavation are visible in the steeply graded hill to the right (Photo by author)*

Figure 6.5 *Brick clinker pile serves as a filter to surface water runoff heading downslope towards the settling pond (Photo by author)*

bricks from the Newcastle plant, which appears at first glance to be a haphazardly placed billboard indicating the industrial past to passing hikers (Figure 6.5). But this location was deliberately chosen in order to provide an ecosystem benefit. The bricks fill a low point between the new wetland and a lower natural pond downhill, providing one final opportunity to filter sediments from stormwater runoff flowing from the compacted soils uphill while limiting further erosion at the low point of the site (Figure 6.3). While a traditional plaque at the entry to the site provides a brief written history of the site, this memorial also provides an example of using waste from the industrial history of the site to actively engage with both visitors and the surrounding ecosystem in a positive way.

Danish Precedents: Nivaagaard and Catherinesminde Teglvaerks

The Pacific Northwest's history with brick dates back to the mid-1800's, with the first signs of local brick production dating back to the 1830's (Gurcke 1987). In contrast to this relatively short history, Denmark has brick buildings from the 12th century that are still in use today (Jensen 2023). This makes the Danish brick industry an interesting region to compare with the Pacific Northwest as it contains both buildings and clay mines that have been exposed to natural and cultural forces for longer periods of time. It also provides the opportunity to learn about the long term impacts of the industry that Seattle will face in the coming decades as its clay mines continue to age. The following two examples are clay mines in Denmark that once provided the raw material for many of the country's landmark buildings, but have since shifted into their second lives as post industrial nature parks.

Nivaagaard Teglvaerks

Over more than 300 years, the brick manufacturing facility at Nivaagaard has evolved from a series of clay pits and ring ovens into a natural preserve for migrating birds and a museum showcasing the industrial history of the site. Located on the coast of the Oresund sea 34 kilometers north of Copenhagen, the site took advantage of the local variety of sediment free red and blue clays in relatively shallow and easily accessible depths. Bricks produced at this facility contributed to the construction of many regional landmarks, highlighted by the grand showcase of Danish masonry skill at P.V. Jensen's Grundtvig Kirke in Copenhagen (Figure 0.3). Excavation at Nivaagaard began in 1701 with a series of small pits near the ring oven (Berthelsen). These expanded into a series of larger coastal and inland pits demarcated by narrow gauge tracks that carried clay from the clay source to the nearby production facility (Figure 6.10). Over centuries of excavation, these sources slowly depleted and brick manufacturing decreased, with the facility eventually ceasing operations in 1981 (Berthelsen).

Present day Nivå is centered around the preserved ring oven, the only remaining ring oven in Denmark and one of only 3 remaining worldwide. It is the central meeting point for visitors and the base of operations for a team of volunteer preservationists who have made concerted efforts to maintain the site since 1985. The preservation of this structure has led to an increased interest in the site, educational opportunities for visitors, and access to government funding to preserve and improve the area. The efforts of the initial preservationists have been the catalyst for preservation of the surrounding area.

Additionally, several recreational activities integrated into the restoration of the site have maintained visitor interest and strengthened preservation opportunities. First, birdwatching has become a popular activity on the site due to its proximity to the sea and the inland lakes formed by clay mining activities (Figure 6.8 and 6.9). This has been encouraged by the addition of bird blinds and observation platforms built by the local government (Figure 6.12). Second, portions of the site have been set aside for tent and RV camping which are regularly used by local residents and distant visitors (Figure 6.11). Adjacent to these campsites is an outdoor playground that includes zip lines connected via a series of platforms mounted to trees (Figure 6.13). And lastly, the walking paths have been set aside as public pathways available to visitors at all times of the year. The proactive addition of these amenities strengthen local residents' connection to the site and can help encourage preservation activities to continue.

Catherinesminde Teglvaerk

Catherinesminde Teglvaerk represents another historic clay mine in Denmark with a history

Figure 6.6 *The brick kiln at Nivaagaard Teglvaerks (Photo courtesy of Leif Tuxon)*

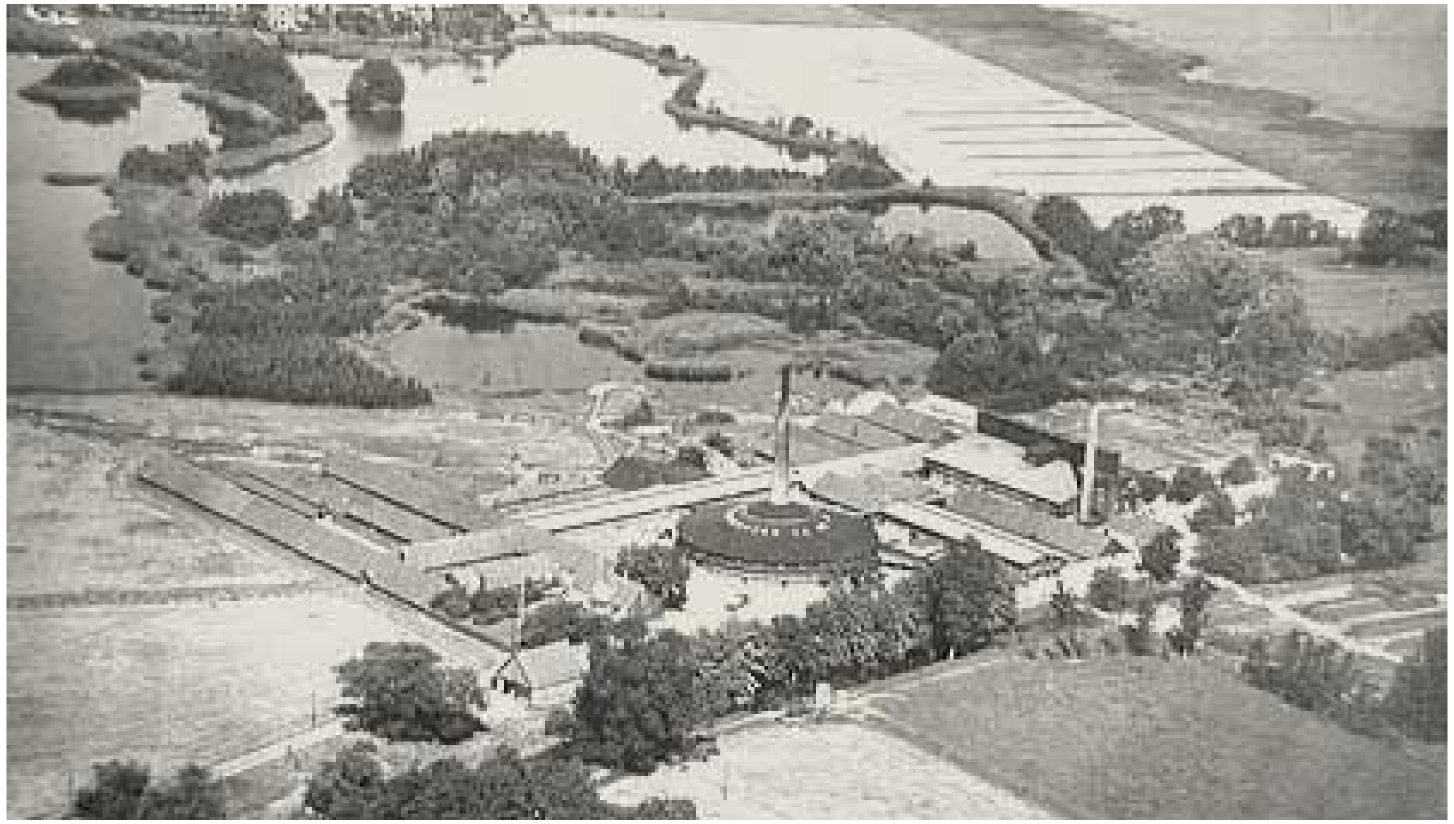

Figure 6.7 *Aerial photograph of Nivaagaard Teglvaerks and surrounding clay mines, many of which are flooded in this image (Photo courtesy of Thomas Lykke Pedersen)*

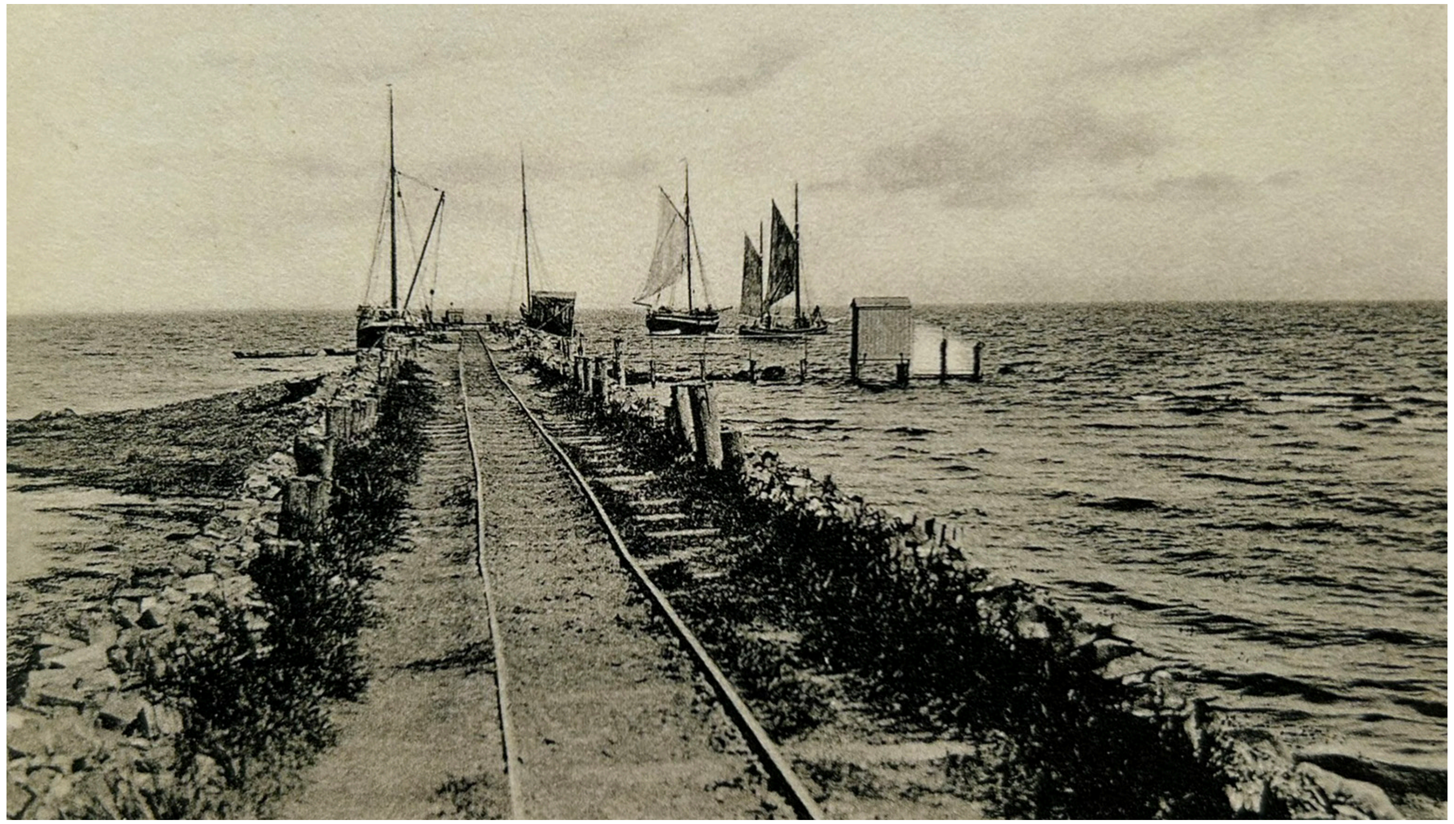

Figure 6.8 *19th century cart tracks stretch along a loading pier into the Oresund Sound, providing direct access to ships harbored nearby that could transport fired bricks to ports across the Baltic Sea (Photo courtesy of Niels-Jørgen Pedersens. 1910)*

Figure 6.9 *Remnants of these original cart tracks are preserved as trails traversing the entire site, conveniently dividing the area into management units for restoration and smaller ponds that attract migrating birds (Photo by author)*

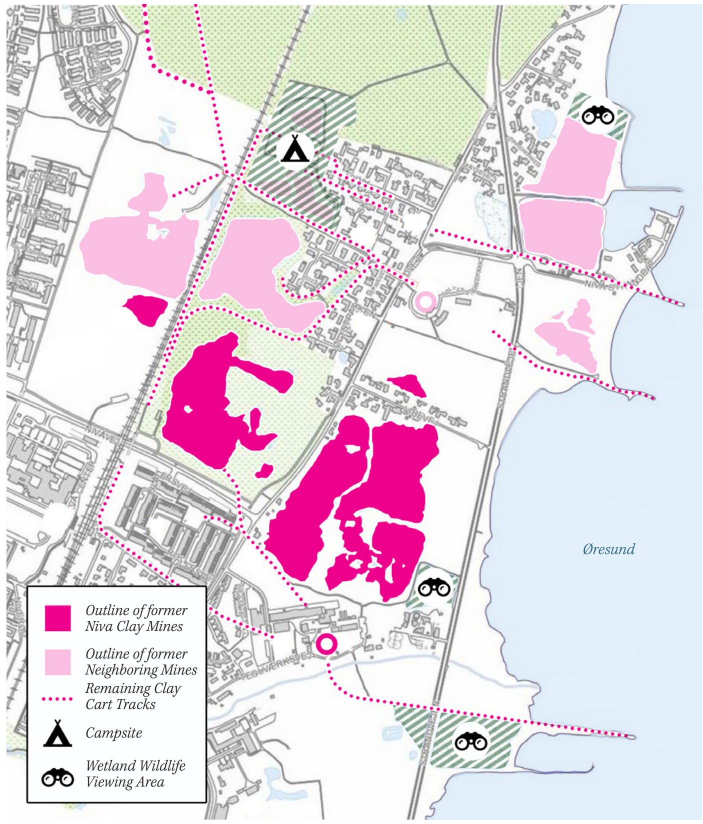

Figure 6.10 *Site plan of the former Nivagaard clay mine. Since closing, the flooded mines have attracted wildlife and outdoor enthusiasts*

Figure 6.11 *Camping sites located among the outlines of former clay mines in the area (Photo courtesy of Nivå Camping)*

Figure 6.12 *Birdwatching platforms built by the municipality have attracted international birding enthusiasts to the site (Photo courtesy of Marie and Torben Lau Floren)*

Figure 6.13 *Obstacle course through the trees provides another outdoor attraction for visitors (Photo courtesy of Phillip Axemann)*

stretching back several centuries. Located in the Flensburg Fjord of southern Jutland, it is one of 60 brick production facilities that sprang up around the clay rich soils of Nybøl Nor lake. As with Seattle, receding ice age glaciers left fine grained clay particles in many locations across the area. The clays left in this portion of the country were particularly valuable due their relative purity and lack of sediment. Brick manufacturing began operations at Catherinesminde in 1732, running for over 200 years until it closed in 1968 ("Oplev Cathrinesminde Teglværk," n.d.).

As with Nivaagaard, the site has been designated as a historic monument for preservation, providing necessary funding from the government that is distributed to Catherinesminde and other culturally protected sites in the region. Also similar to Nivaagaard, the visitor experience is centered around a preserved tunnel kiln and ancillary buildings involved in the production of bricks. Tour guides are available to lead visitors through the site, which can include reenactments of the retired industrial practices that occurred.

The landscape restoration provides unique elements that more subtly reference the industrial past. Similarly to Nivå, a series of hiking trails are interlaced across the site, working with the remnants of the industrially graded topography in the area. Along these pathways are a series of sculptures made of brick that reference the history of the area while modernizing it with contemporary artists (Figure 6.14 and 6.16). They also provide helpful wayfinding devices while traversing the many trails. The addition of these features further help to provide a contemporary flourish and connection with a place rather than leaving it purely frozen in time.

Potential Applications for Seattle Urban Clay Mine Restoration

A review of these three mine restoration projects provides a variety of both domestic and international references for successful strategies that can potentially be implemented in the Seattle context to improve long term restoration results.

The restoration efforts at Cougar Mountain provide insight into a similar ecosystem as the Duwamish River Valley mines, which is a valuable reference for the native plant selection. It also provides inspiration for low-budget solutions that reference the industrial history of the site while utilizing locally available discarded bricks as a solution for stormwater mitigation. A Seattle-based solution should catalog existing materials that are available to restoration efforts and determine methods for implementing them into the wider goals of the project.

The two Danish examples are in a different ecosystem than the Pacific Northwest, but their efforts to engage the community by encouraging interactions with wildlife and the environment are internationally relevant and worthwhile efforts to experiment with in the Seattle context. Specifically, the Catherinesminde example goes even further by reaching out to the local art community to inject more contemporary interventions into the site, which is another opportunity that could be considered in the Duwamish River Valley. Both of these solutions have the potential to encourage more visitors to explore the site and create long term connections with the community that extend beyond industrial memorialization.

Chapter 8 combines these field proven strategies with recommendations found in Seattle-based guidebooks for restoration practices. This combines the opportunities found in these case studies along with the critically important regional ecological information that takes into account local flora, fauna and geology.

Figure 6.14 *Brick sculptures by local artists found along the interpretive walking trail through the former Catherinesminde clay mine (Photo by author)*

Figure 6.15 *Photograph of Catherinesminde Teglvaerk from the shores of Nybol Nor (Photo courtesy of Museum Sønderjylland)*

Figure 6.16 *Stormwater structure built from salvaged bricks near Catherinesminde Teglvaerk in Broager, Denmark (Photo by author)*

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Figure 7.1 *Exterior photograph of the Resource Rows repurposed masonry facade. Completed in 2020 by Lendager Architects in Copenhagen (Photo courtesy of Lendager Architects)*

Chapter 7

Case Studies - Innovations in Brick

This chapter explores recent innovations in the brick manufacturing and construction process that further emphasize the circular characteristics of the material. It first considers construction waste as an alternative to raw clay in bricks, presenting several case studies that repurpose this universally growing waste stream. It then focuses on potential alternatives to cement mortar that also allow for disassembly and reuse.

7.1 MATERIAL MAKEUP - CONSTRUCTION WASTE

Construction and demolition (C&D) waste accounts for a growing amount of landfill material that is causing increasing pressure on global economies and environments. In the United States, this amount has grown from 135 million tons in 1990 to more than 600 million tons in 2018, accounting for more than twice as much material as municipal solid waste (US EPA 2017). According to the EPA, only 20% of gypsum, asphalt shingles, and brick and clay tiles are recycled in comparison to 80% of concrete, steel and asphalt (Cho, Asmar, and Aldaaja 2022). Research into methods that repurpose these specific materials provides a valuable opportunity for the industry to limit the strain on landfills, extend the lifespan of the embedded energy in these products, and create opportunities for economic development. Brick is an ideal building material for repurposing construction waste, as the existing production methods utilize bound aggregates and the relatively simple profiles of bricks can be replicated with alternatives to traditional clay. By taking advantage of these local waste streams that are omnipresent in large cities, transportation costs between production facilities and final construction site can also be limited.

Figure 7.2 *Existing masonry walls at the former Carlsberg factory permanently bound with cement mortar are cut into panels and repurposed into a quilted facade at Resource Rows in Copenhagen, Denmark by Lendager Architects (Photo courtesy of Lendager Architects)*

Repurposed Bricks - Gamle Mursten & Resource Rows

Prior to considering the creation of new bricks from construction waste, it is worth noting the opportunities to reuse existing bricks from demolished masonry buildings. As noted above, only 20% of brick and clay tile is recycled in the United States, despite the extensive lifespan of fired clay bricks that can last hundreds of years. In addition, each repurposed brick can save 500 grams of CO2 compared to traditional manufacturing processes (Gamle Mursten, n.d.).

It is a common practice in many European countries to repurpose bricks, as they have an extensive building stock of aging brick buildings to pull from. Denmark alone reuses 3 million bricks each year (Santoro 2020). The Danish company Gamle Mursten specializes in techniques to prepare recovered bricks for a second life. They utilized a process called “vibrational rasping” that shakes and scrapes old mortar from the recovered bricks without the need for water or chemical additives (Gamle Mursten, n.d.) (Figure 7.3). The bricks are sorted and tested for performance, leaving their facility with an officially recognized conformité européenne (CE) stamp that confirms their suitability for new construction. An average of 50% of the bricks recovered from a demolished building can be recovered with this method (Braam 2020).

Unfortunately, this process is only an option for brick buildings that have been assembled with lime based mortars. As noted in previous chapters, cement

Figure 7.3 *Inspecting harvested bricks at Gamle Mursten (Photo courtesy of Gamle Mursten)*

based mortars create a permanent bond that is far more difficult to remove without damaging the brick itself. In the United States, construction practices shifted towards cement-based mortars in the 1940's, resulting in a limited stock of masonry buildings that are viable for disassembly.

There is one additional option for repurposing existing bricks bound with cement, exemplified by the Resource Rows project in Copenhagen (Figure 7.1 and Figure 7.2). Completed in 2020 by the local firm Lendager Architects, this housing development repurposes cement mortar-bound bricks by cutting the existing facade into 1m x 1m panels and converting these into prefabricated envelope elements (Lendager 2020). The panels are sourced from the former Carlsberg Factory, transporting the embedded energy of the building materials along with the built-in social history and physical patina of a well known building. This option is design intensive, but provides one more outlet for repurposing brick material that would otherwise become aggregate or be sent to the landfill.

Fired Bricks - Waste Based Bricks

There has been significant research into repurposing construction materials in the brick production process (Zhang et al. 2018), and several have graduated from experimental to market-ready products. One of the more promising and successful examples is FRONT (formerly StoneCycling), a Dutch company founded in 2015 that produces sustainable building materials which limit raw material extraction and redirect existing waste streams towards new material production. Their first flagship product, WasteBasedBricks, replaces the raw clay used in traditional brick manufacturing with more than 60% construction waste (Figure 7.4). The waste is primarily composed of roof tiles, old bricks, and glass powder that has been ground into a fine aggregate (Kuiper 2024). This substrate is then introduced back into the traditional brick manufacturing process, as it is formed into individual blocks, dried, and heated in a kiln. Due to the alternative waste substrates being used, the kiln can be heated to a lower temperature than typical brick, lowering the overall energy input in

Figure 7.4 *Waste Based Bricks by FRONT (formerly StoneCycling) utilize >60% construction waste in their production, reducing the need for raw clay and diverting waste from landfills (Photo courtesy of FRONT)*

Figure 7.5 *Waste Based Bricks utilized as an exterior facade in the new Technique office space in Clerkenwell, London by Buckley Gray Yeoman Architects. The bricks are responsible for upcycling 22,080 kg of waste material (Photo courtesy of Jack Hobhouse)*

the production phase (Kuiper 2024). While production is still reliant on natural gas, the company is aiming to shift to a hydrogen fueled kiln in the coming years in order to further reduce the carbon footprint of the material.

While repurposed bricks allow for the imported history and patina of the material to last through multiple life cycles, WasteBasedBricks give designers more of an opportunity to imbue their own imaginations into the final product. StoneCycling's experiments with different waste substrates and glazing materials has produced a wide range of finishes that offers designers flexibility to incorporate waste into their projects. They are also developing projects utilizing waste material from buildings that previously occupied the same site, allowing its material history to live in situ through a new building. This strategy permits these waste-based materials to "speak" of their past with inhabitants and visitors, providing an important opportunity in educating the general public about waste management and CE design.

Unfired Bricks - K-BRIQ

The Scottish company Kenoteq has recently developed a product, K-Briq, that entirely avoids the firing process of traditional brick production while replacing clay with up to 95% construction waste (Black 2024). Their bricks are composed of recycled drywall, rubble, concrete, and mortar, held together by a proprietary binding agent. This mixture is formed into molds that are hydraulically pressed, removing air gaps and compressing the material into its final shape. By avoiding traditional firing and vitrification of clay, K-Briq eliminates the primary carbon emitting stage of the production process by using 1/10th of the energy and less than 5% of the carbon footprint (Figure 4.14, Black 2024).

The addition of drywall to the mixture provides a repository for another waste stream that is difficult to recycle in the United States. Drywall is composed of gypsum, which has binding properties very similar to plaster and is advantageous in an unfired production process. Recycled pigments provide the final finish coloring, which ranging from traditional clay-like tones to bright shades of pink, yellow and blue (Figure 7.6). The extruded production process creates a more uniform color tone and less naturally textured finish than a traditional fired clay brick. But the option to use these striking colors and announce the material as something contemporary and different may be a more valuable opportunity in terms of public engagement and education about waste cycles (Figure 7.7).

7.2 ADAPTABLE ASSEMBLIES

Alternatives to Cement Based Mortars

While brick production is responsible for the embedded energy within an individual unit, it is the construction method that determines the overall lifespan potential of the material. The current industry standard of cement mortar permanently binds bricks together, eliminating opportunities to take advantage of the material's extensive lifespan. The following examples illustrate alternative construction methods that improve the prospects for the disassembly and reuse of brick.

Lime Mortar

As with many circular design attributes, it is best to look back in time to find the materials and construction methods that are most conducive to Cradle-to-Cradle construction processes (McDonough and Braungart 2002). The history and advantages of lime-based mortars were discussed in detail in Chapter 4. This section instead focuses on current barriers and potential gateways to reintroducing the benefits of lime-based mortars into the bricklaying industry in the Pacific Northwest.

Mortar specification in the United States is based on ASTM C270, Standard Specification for Mortar for Unit Masonry, which separates the material into the fours types listed in Figure 7.8 (Brick Industry Association 2020; "ASTM C270: Standard Specification for Mortar for Unit Masonry" 2010):

These specifications make it apparent that increasing the hydrated lime content leads to a decrease in compressive strength, which can lead to a wariness to specify mortars with high lime content ("ASTM C270: Standard Specification for Mortar for Unit Masonry" 2010). In addition, the shift from mass masonry to slim veneer walls and considerations for wind and seismic loads imply a need for additional mortar strength, which further complicates this specification. However, additional testing has

Figure 7.6 *K-BRIQ by Kenotech, based out of Edinburgh, Scotland, utilize >95% construction waste in a non-fired production process (Photo courtesy of Kenotech)*

Figure 7.7 *Rendering of a proposed project by Springfield Properties PLC that utilizes the full range of K-BRIQ's color line in its facade, creating a playful focal point that draws attention to the entry of the building (Photo courtesy of The Springfield Group and Kenotech)*

indicated that masonry veneer walls are currently overdesigned, and that they are more reliant upon their anchors rather than the mortar specification when experiencing seismic lateral load (Farny 2012). Despite recommendations to select mortar with the least amount of compressive strength required, there are elements of the industry that revert to a "the stronger the better" mentality in order to limit the risk of structural failures. However, this is not the case with masonry, in which the mortar must always be weaker than the bricks in order to control cracking and limit spalling.

Another barrier to specifying traditional lime mortars is the lack of installers experienced with the material. Traditional lime has different consistencies, ratios and set times compared with contemporary mortar, requiring a more developed skill set in order to properly install. Those who do have the necessary experience are generally limited to historic preservation projects, which reflects a wider separation within the industry (Hamel, 2024). The increased mortar setting time and need for specialized bricklayer skills inevitably leads to an increase in cost, which may be the primary barrier to specifying traditional lime mortar.

With that being said, the British Brick Development Association has begun to recognize the increasing use of cement-free hydraulic lime mortars on new construction products in the pursuit of sustainable objectives (Brick Development Association 2023). They note that there are no masonry standards in place for this choice, and at this point designers are recommended to work directly with masonry and lime manufacturers in order to ensure the proper mix. This puts the impetus on architects and designers to continue experimenting with non-cement mortars in order to put pressure on the masonry associations to provide additional specifications for traditional hydraulic mortars. The expansion of hydraulic mortar specifications could have exponential impacts on the industry, increasing the material's exposure to inexperienced bricklayers and the wider public, who have less resources to be able to research and specify bespoke mortar mixes on individual projects.

Mechanical Fasteners

While there are potential legislative hurdles to overcome in order to take advantage of cement-free mortars, mechanically fastened masonry provides an alternative route that can provide the same or better opportunities to salvage bricks at the end of a building's operable life cycle. Rather than rely upon a chemical bond between brick units, mechanical fasteners utilize pre-manufactured clips that connect each individual brick to a bonded whole. Eliminating mortar can lead to a major reduction in installation time, as the mortar mixing and cleanup process is time intensive and highly susceptible to delays from weather related requirements. Mechanical fasteners may require additional design up front by architects to coordinate the system's interface with the wall, but it can also simplify installation in the field without the need for highly specialized craftspeople.

A practical solution using this strategy is offered by Wienerberger, Europe's largest masonry supplier, and their cladding system called ClickBrick which combines a unique brick profile with a metal fastening system to mechanically mount masonry veneer to a structural wall backing wall (Figure 7.9 and Figure 7.10). The product is commercially available and has been used on more than 40 projects since its launch in 2022 (Bierens and Jansen 2024). While the use of steel fasteners carries with it a high embodied energy, this is

Mortar Type	Compressive Strength	Cement / Lime Ratio	Common Uses
N	750 psi	1 / 0.50-1.25	General Purpose, Good Bonding and Working Capabilities
S	1,800 psi	1 / 0.25-0.50	General Purpose, High Compressive and Flexural Strength
M	2,500 psi	1 / 0.25	High Compressive Strength, Poor Workability
O	350 psi	1 / 1.25-2.50	Low Strength Mortar for Interiors and Restoration Work

Figure 7.8 *Mortar strength table (Adapted from ASTM C270: Standard Specification for Mortar Unit Masonry)*

Figure 7.9 *ClickBrick mechanical fastener components (Photo courtesy of Wienerberger)*

Figure 7.10 *ClickBrick installation detail with masonry anchors tied back through a layer of continuous exterior insulation (Photo courtesy of Wienerberger)*

generally balanced by the removal of cement mortars that can represent as much as 20% of a wall surface in a traditional masonry assembly. The fasteners also carry with them a 50% decrease in installation time, delivering a significant financial benefit in the face of increasing labor costs (Bierens and Jansen 2024).

Click Brick evolved from Cube Brick, which launched over 20 years ago with the same fastening system. Wienerberger purchased the company in 2020 and refined the product to make it more marketable. First, they shifted from an extruded to a waterstruck production process, which gave the brick a more handcrafted look that appeals to the residential market. They also added a continuous indentation along the top of each unit to provide a faux shadow line. This makes the wall appear as individual bricks rather than a mass wall of clay. Their final change was to insist that vertical expansion joints continue to be used per existing standard masonry building codes, as they noticed that their inclusion limited horizontal separation of each unit as the building settled over time. These improvements have made Click Brick more appealing to a wider sector of the industry, and also allows them to refer to the positive 20 year track record of the Cube Brick product in order to feel confident with its durability over time.

The challenge with this system is maintaining the aesthetic appeal of on-site craftsmanship that is prevalent in many beloved historic brick buildings. The system is generally limited to vertical walls in a single plane, but it is possible to alter the depths of the masonry anchors if coordinated with the manufacturer. One alternative to this may be to combine it with other material systems that provide more ornamental flourish, while the ClickBrick system fills in the majority of the remaining wall surface.

Assembly Cover Cladding

Lime mortar and mechanical fasteners provide viable methods for repurposing brick, reintroducing one of the historic advantages of the material. But there is a wider question to ponder: why should we continue to use traditionally dimensioned bricks at all if they are simply serving as a rain screen rather than a structural wall. There are lighter and less expensive materials that can provide similar levels of climate control. Brick "slips" - bricks trimmed into a thinner dimension and grouted directly to an exterior wall surface - use less material, but they are also permanently bound to the wall and so lose the ability to be repurposed.

Danish architecture firm Lundgaard & Tranberg worked with brickmaker Petersen Tegl and addressed this question in their development of the "Assembly Cover" cladding system. It is a larger format clay tile that maintains the fired clay finish of traditional brick, but revises the profile to create a thinner profile that limits installation time, eliminates mortar in favor of a simple cladding system, and provides the opportunity for future disassembly. Produced in a wide U-shape, the cladding is fastened to wood furring strips with metal fasteners (Figure 7.12). The cladding is installed in courses with overlapping profiles, creating a similar shadow line seen between courses of brick and mortar walls.

The similarities between the materials are exemplified in the Kannikegården project in Ribe, Denmark (Figure 1.1 and Figure 7.11). Lundgaard & Tranberg were tasked with creating a history museum over the ruins of the oldest brick church in Denmark, while also providing annex space for the neighboring church. They aimed to make a reference to the cultural tradition of brick, but also to provide a contemporary form and use of the material that was appropriate for the 21st century. The result is a clean lined facade with contemporary window openings that still references the scale and form of adjacent buildings. But it is the material finish that fully emphasizes the connection between historic and contemporary, maintaining the same clay patina on display in the surrounding buildings.

This material provides an interesting option for owners and designers interested in creating the feel of a traditional brick building but with the advantages of disassembly and decreased installation time. This project and a similar finish at the Soro Art Musuem spurred many other designers in Scandinavia to use this option, as well as some manufacturers to produce a less expensive but less handcrafted version of the product. And while each cladding unit can be easily disassembled, the updated dimensions lack the versatility of traditional brick as its next life is limited to the same type of installation and use as an exterior cladding.

Figure 7.11 *Kannikegården in Ribe, Denmark. Designed by Lundgaard & Tranberg Architects, completed in 2015 (Photo courtesy of Anders Sune Berg)*

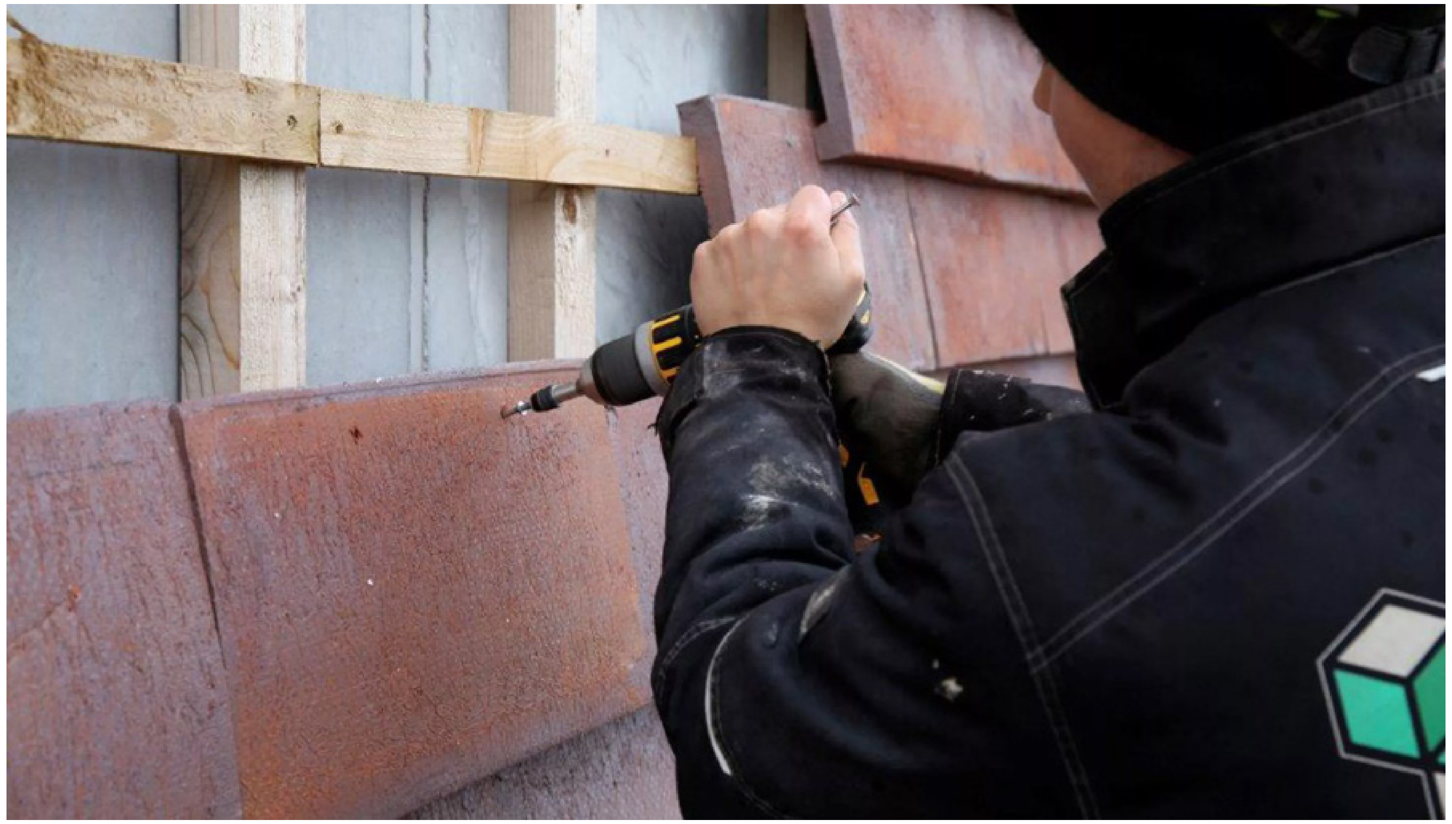

Figure 7.12 *Installing with metal screws fastened through pre-drilled holes in the clay cladding and into wood furring strips beyond (Photo courtesy of Petersen Tegl)*

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Figure 8.1 *An array of sample mixtures testing which ratios of repurposed construction and industrial waste produce the best brick alternative to raw fired clay (Photo by author)*

Chapter 8

Applying Combined Approaches

This research introduced an outline of the current issues facing the brick industry, followed by a historical summary of how we arrived at this point, and most recently a review of existing case studies that provide proven methods for improvement. Chapter 8 builds upon those case studies to present a combined approach that addresses the historic shortcomings and future opportunities of brick across its extraction, production, and construction processes.

First, a clay mine restoration toolkit provides a visual compendium of coordinated reference material for urban areas along the Duwamish River valley that still bear the impacts of clay excavation. Next, experiments with full scale physical mockups propose bricks composed of internationally available and contextually specific materials (Figure 8.1). The profile of the brick is designed in conjunction with a fastening system that provides an alternative to cement-based mortars, improving the material's opportunity for disassembly and reuse. These interventions aim to create an exponentially improved material that addresses multiple life cycle stages within the potential lifespan of a brick.

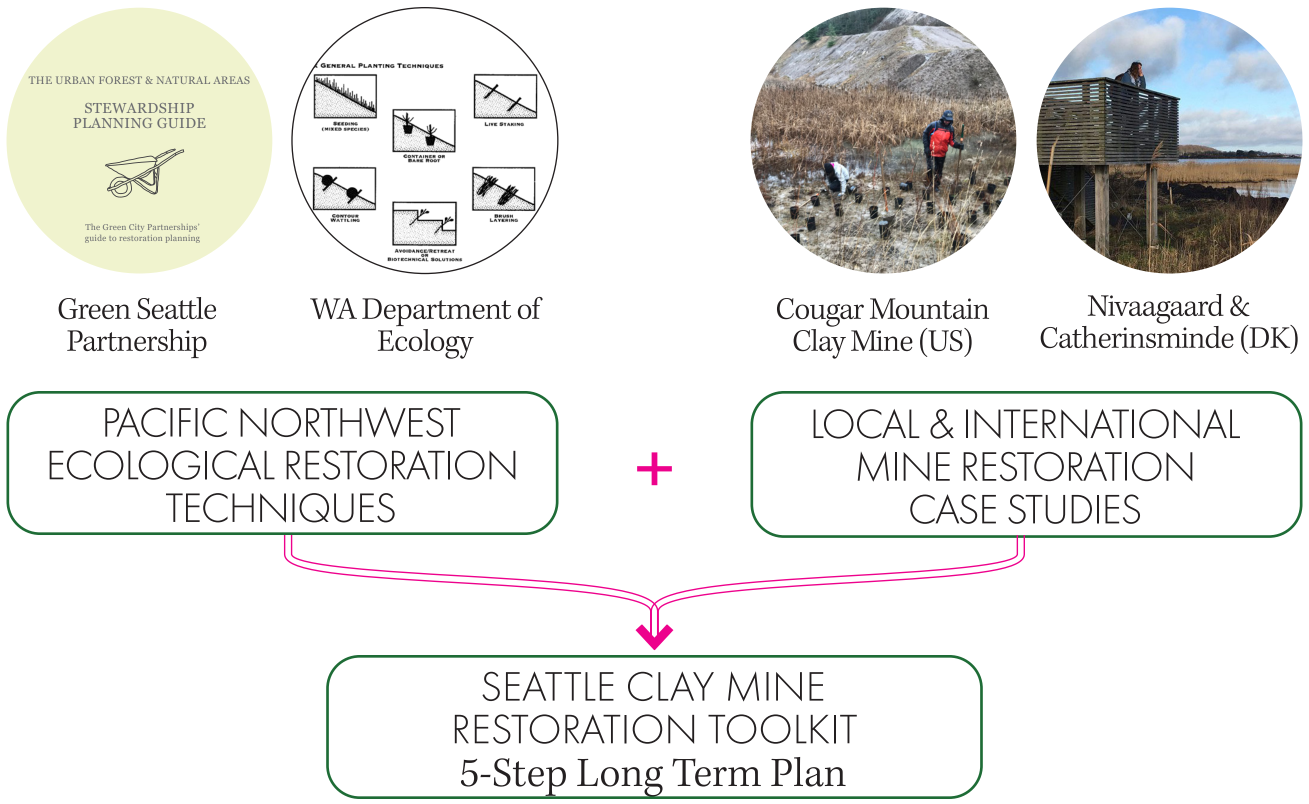


Figure 8.2 *Research methodology leading to a final Seattle Clay Mine Restoration Toolkit, which combines variety of regionally specific restoration techniques with relevant case studies from the United States and abroad (Diagram by author)*

8.1 SEATTLE CLAY MINE RESTORATION TOOLKIT

Despite the number of clay mines within the urban limits of Seattle and the conflicts they create with local residents and wildlife, there is currently no coordinated strategy for restoring these sites. Increased susceptibility to erosion has created steep cliffs that pose a risk to adjacent neighborhoods, and compacted soils prevent the establishment of native plants. These impediments limit opportunities for public green space that could otherwise serve as an amenity for residents and a refuge for wildlife in a rapidly densifying city.

The following section illustrates a toolkit for restoring these sites with strategies that are specific to the region in order to provide the greatest impact on residents, soil health and wildlife (Figure 8.2). Existing ecological restoration research is used as a blueprint for the toolkit, separating the planning into five stages: planning for restoration, soil stabilization, soil restoration, plant selection and removal, and continued maintenance. Regional guidelines regarding landscape restoration and inspiration from Chapter 6 case studies are integrated into these stages. The toolkit is represented visually in order to provide wider accessibility to the general public.

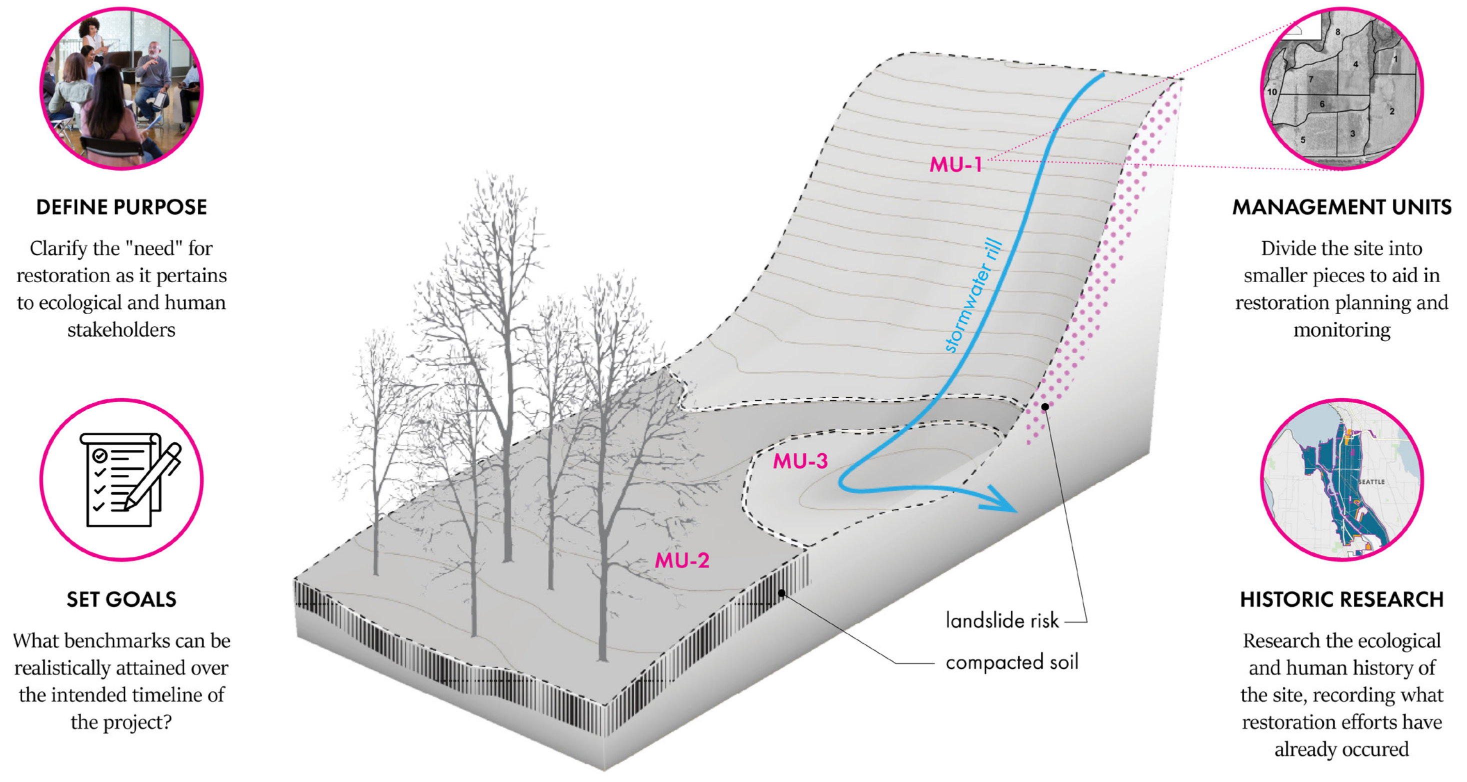


Figure 8.3 *Toolkit Step #1: Planning for Restoration (Image by author)*

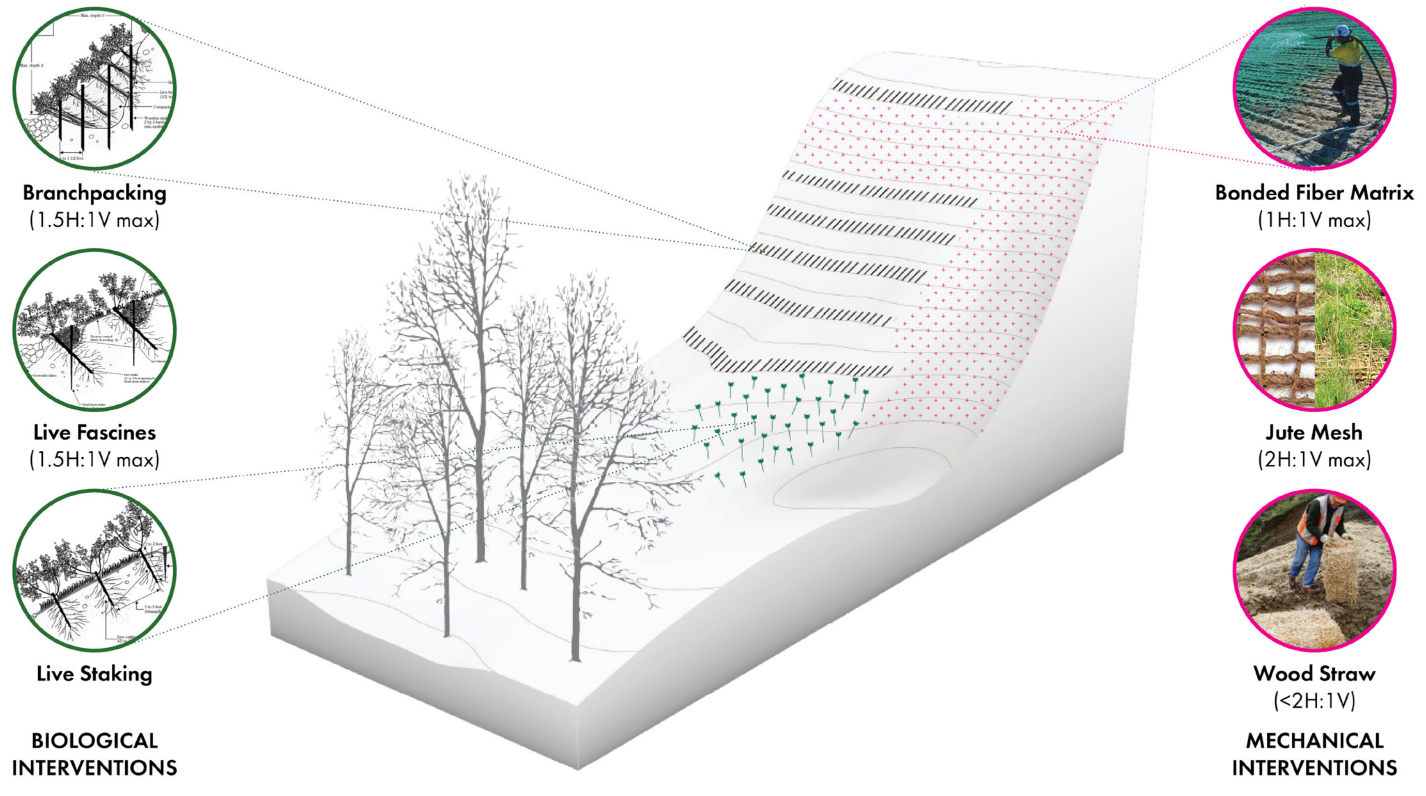


Figure 8.4 *Toolkit Step #2: Soil Stabilization (Image by author)*

Planning for Restoration

Chapter 6 highlighted research indicating that ecological restoration is most effective when it has a clearly defined purpose and goal at the outset of the project (Cooke and Johnson 2002; Martín Duque et al. 2021; Turrión et al. 2021; "Stewardship Planning Guide" 2014). This initial process requires stakeholders to ask themselves a number of questions, beginning with addressing the need for restoration and who or what will benefit from it (Figure 8.3). The stakeholder group should also set specific goals for the project, primarily determining what level of restoration is called for. This can range from a recreation of pre-settler conditions to a fully new ecotype more suited to present day conditions. And lastly, a timeline for the restoration should be integrated into the project that indicates specific benchmarks to be accomplished throughout the process.

It is important to perform ample research on the history of the area in order to diagnose an effective and appropriate solution which addresses ecological and cultural needs of the site. This can include an inventory of existing plants, wildlife, and soil types across the site, as well as human activity that takes place in the area. In the case of former mines, this includes researching what areas have been primarily shaped by human rather than natural activity.

In order to simplify this process, it is recommended to divide the site into a series of smaller management units ("Stewardship Planning Guide" 2014). Restoration sites are often expansive, and by splitting the area into smaller parcels with similar characteristics, more specific and effective management plans can be arranged. This aids with initial data collection as well as future site monitoring.

Soil Stabilization

Due to the steep slopes created by clay mining activity along the Duwamish valley, some of the first interventions to take place on the site should be focused on soil stabilization (Figure 8.4). This addresses the safety concerns in the area, while providing more amenable soil conditions for the plants to take root. Interventions can be biological, utilizing the natural stabilizing properties of plants and their root systems, or mechanical, incorporating more engineered solutions.

Biological solutions include various methods of staking plant roots into prepared areas of a steeply sloped site. The goal is that these roots will eventually grow into soil, providing a natural "rebar" that holds the earth in place against erosive forces. These interventions evolve as natural elements of the site which improve with time. However, they can take longer to establish effectively and they can only be installed at certain times of the year. There are certain types of plants well suited to soil stabilization, as they have rapidly growing and deep set root systems that improve the reinforcement of the slope. A list of recommended plants and additional installation guidelines can be found in a manual produced by the Washington Department of Ecology, "Slope Stabilization and Erosion Control Using Vegetation" (1993).

Mechanical interventions are generally more engineered solutions that provide more immediate benefits to slope stabilization, but are not intended to last for long periods of time. They can often be specified for locations with particularly steep slopes that cannot be addressed with a biological solution.

A final method to consider is soil buttressing, which adds a large mass to the base of a slope in order to reinforce the soil and prevent landslides. Often seen as a retaining wall structure, it can also take the form of additional soil piled up at the base of a slope. One experimental method could utilize demolished bricks from Seattle buildings as a soil buttress. Similar to the efforts at Cougar Mountain, the incorporation of bricks as an ecological restoration tool offers a multi-benefit solution: stabilizing the slope, providing pockets of air space for root growth, redirecting construction waste from landfills, and creating a visual reference of the site's industrial past to visitors.

Soil Restoration

Once there is a plan in motion to stabilize the steep slopes, strategies that improve the health of the soil can begin (Figure 8.5). These approaches can be separated into methods that provide external protection of the soil, or they can target improving the chemical composition of the soil itself.

External protection of the soil can be achieved through mulching and water dispersion. These surface

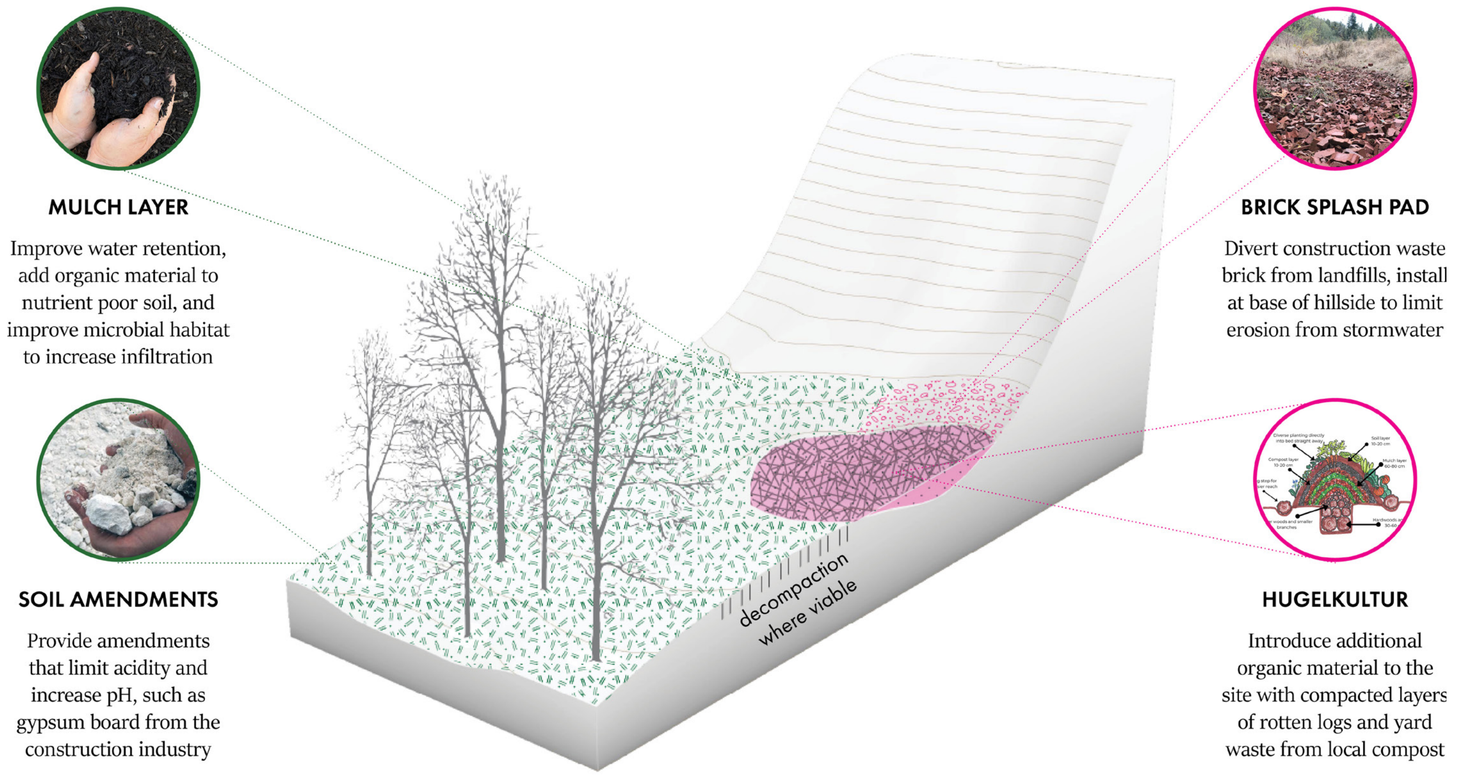


Figure 8.5 *Toolkit Step #3: Soil Restoration (Image by author)*

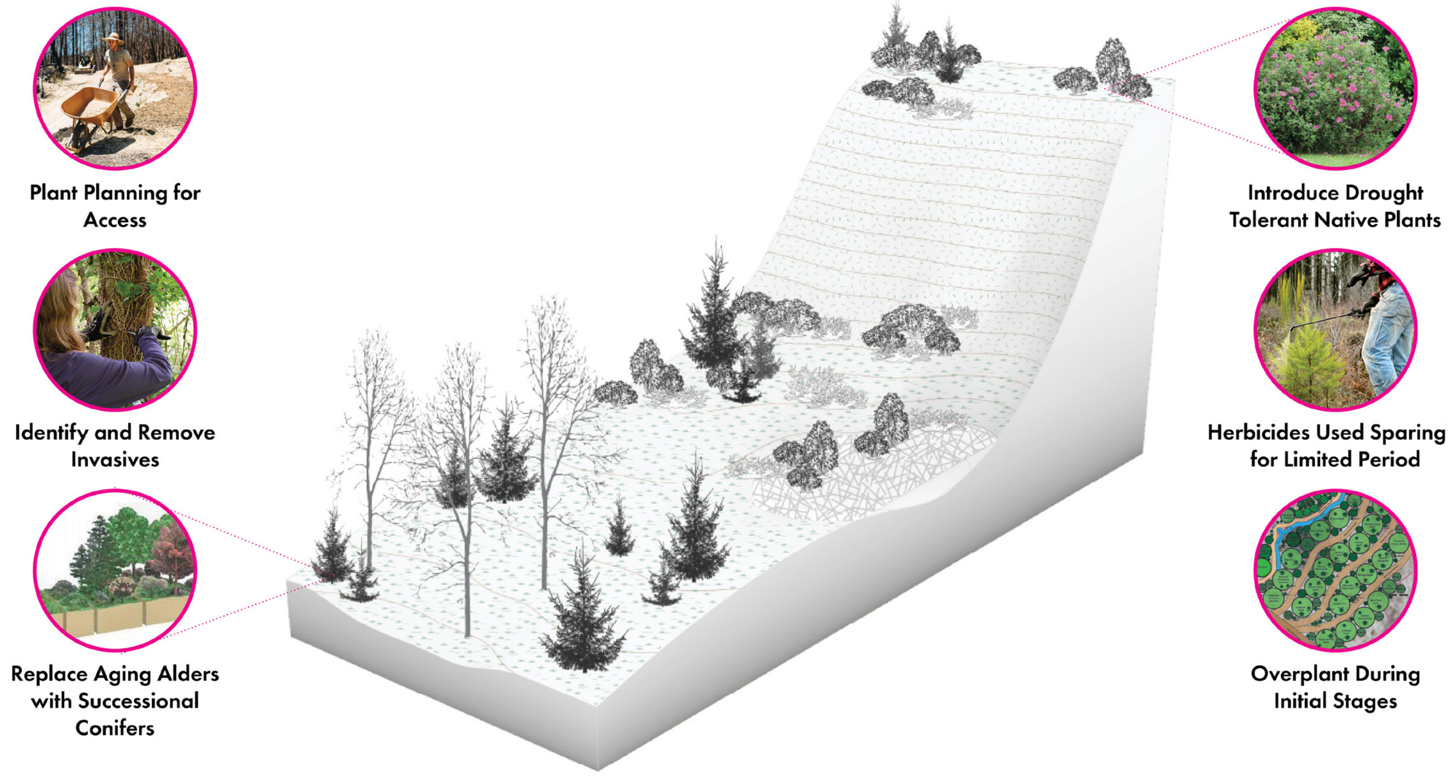


Figure 8.6 *Toolkit Step #4: Plant Removal, Replacements and Additions (Image by author)*

level strategies help limit erosion caused by humans, wind, and rain. Water dispersion can come in the form of recovered brick splash pads placed in existing rills where stormwater runoff can be particularly erosive. Mulch also provides an external barrier to the exposed soil below. But the surface application of mulch also improves water retention of the soil, and as it decomposes it leaches nutrients into the NPK-deficient soil below. The decomposing mulch also improves microbial habitats, which in turn increases soil porosity and improves water infiltration through the compacted soil.

The addition of soil amendments to a mulch mix supplies additional benefits that more directly address nutrient deficiencies and pH imbalances on the site. One example, gypsum, is a commonly available material well known for its ability to limit acidity and increase pH in agricultural applications. This characteristic is helpful on former clay mine sites, which are frequently acidic due to the lack of nutrient cycling taking place. The ubiquity of gypsum and opportunities to redirect it from landfills provides added incentive for integration in a restoration strategy.

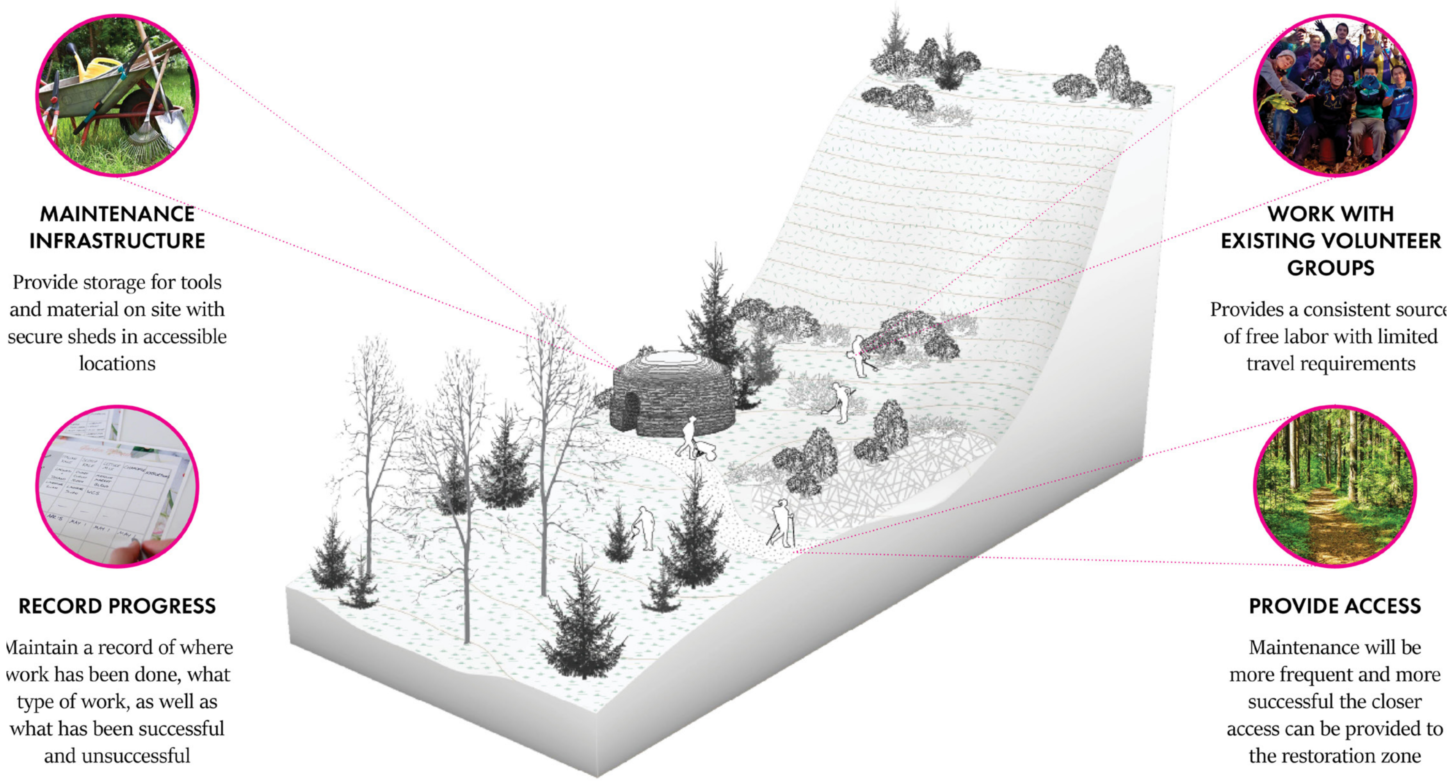
And finally, when it comes to filling low points that have been eroded by stormwater runoff, hugelkultur practices can be used to create a healthy soil crafted from woody debris gathered on site. This compostable material could be concentrated in one location and mounded up to create a small hillock before it is covered with topsoil. Over time the compostable material below decomposes and releases its nutrients. It also provides an excellent growing medium for the establishment of new plants.

Plant Removal, Replacement & Additions

Decisions regarding plant removal, replacement, and additions will have a lasting impact on a site, particularly after steps have been taken to improve the soil health and stability (Figure 8.6). Many of these Duwamish clay mine sites have been overtaken by invasive species, therefore the first step is to remove these from the site. Specifically, English ivy and Himalayan blackberry present the most common and most challenge for removal. It requires multiple seasons of diligent work in order to fully eradicate them. While herbicides are not an ideal solution, they are necessary when working on sites of this scale, particularly in areas with difficult access and limited funding (Lund 2023). But herbicide use can be limited to spot treatment for the first few seasons before new plantings help to crowd out the invasive growth, after which herbicide use can be reduced or eliminated.

New plant selections should strive towards native species that work in concert to improve biodiversity and soil health. For example, the current monoculture of alders that exist on site can be thinned down, replacing aging trees with successional species of drought tolerant conifers in areas that have access to sunlight. This downed alder and other understory debris can be collected for use in hugelkultur applications elsewhere on site. Understory plant selections should strive to be native species that are also adaptable to the increasing frequency of droughts and high temperatures. This means that commonly seen plants, such as native sword ferns, could begin to be replaced by other species that can handle the hotter and drier conditions that are expected in the coming years due to climate change. Some of these selections may not fall within the previously held notions of Pacific Northwest native plant types, but in order to improve their chances of success these expectations will have to become more malleable. Therefore plant lists from Oregon and Northern California may become better references in the coming decades as hardiness regions inevitably trend northward.

The success rates of these species can be increased by planting them in the appropriate conditions, referencing the micro conditions logged within each defined management unit to determine which plant community should be located and when it should be introduced. Overplanting the initial installation of plants is a strategy that can be used in anticipation of inevitable dieback. And finally, planting layouts should consider how maintenance pathways will impact their layout. Plants that require more diligent maintenance can be located closer to pathways in order to facilitate their early growth.



MAINTENANCE INFRASTRUCTURE

Provide storage for tools and material on site with secure sheds in accessible locations

RECORD PROGRESS

aintain a record of where work has been done, what type of work, as well as what has been successful and unsuccessful

WORK WITH EXISTING VOLUNTEER GROUPS

Provides a consistent sourc of free labor with limited travel requirements

PROVIDE ACCESS

Maintenance will be more frequent and more successful the closer access can be provided to the restoration zone

Figure 8.7 *Toolkit Step #5: Planning for Continued Maintenance (Image by author)*

Planning for Continued Maintenance

An often overlooked element of any landscape design, planning for the continued maintenance of mine restoration sites is absolutely vital towards the success of the project (Figure 8.7). As noted by Cooke and Johnson, restoration should not be considered a final state of accomplishment but instead a continuous process (Cooke and Johnson 2002). In order to improve the upkeep of the site, there are several methods which can be incorporated into planning ranging from tangible to community based elements.

First, physical site resources such as maintenance infrastructure and accessible pathways must be incorporated into early stages of the restoration planning. Strategic placement of covered sheds for storing equipment and soil amendments can drastically limit the amount of effort required to move materials around on site. And pathways for both maintenance and recreational visitors should be considered, establishing a balance between access for maintenance personnel and chances that visitors will wander off paths and potentially damage plants.

Less tangible elements like volunteer coordination and record keeping are also important to the continued success of a restoration project. Fortunately for the abandoned clay mines of Seattle, their direct proximity to densely populated neighborhoods provides abundant opportunity for volunteer recruitment. There is an established network of groups in the Seattle area, such as the Green Seattle Partnership (GSP), that can be tapped for their valuable knowledge and connections with potential volunteers (Green Seattle Partnership 2017). GSP is already engaged in the monitoring and upkeep of over 50% of Seattle's public forestland, including portions of the North Beacon Hill Greenbelt that are adjacent to abandoned clay mines. This experienced group also has the capacity for record keeping of maintenance progress, which is important for long term projects that will see many changing hands over time. Record keeping is important for cataloging progress, identifying areas for improvement, and maintaining reminders about the initial goals of the project throughout its lifespan.

Findings

Integrating these ecological restoration strategies into a coordinated plan for the improvement of the abandoned clay mines of the Duwamish River valley presents a very feasible and exciting opportunity that local residents, wildlife, and the wider ecosystem can benefit from. The introduction of a linear park stringing these spaces together would provide major stormwater, ecosystem, and social benefits to an area that is currently sitting dormant. The green space could provide a safe haven for numerous birds and mammals currently pushed out by increased development as well as a green connection between neighborhoods. And by integrating elements that reference the brick industry which previously inhabited the site, connections between our natural landscapes and built environment can be shared with the community.

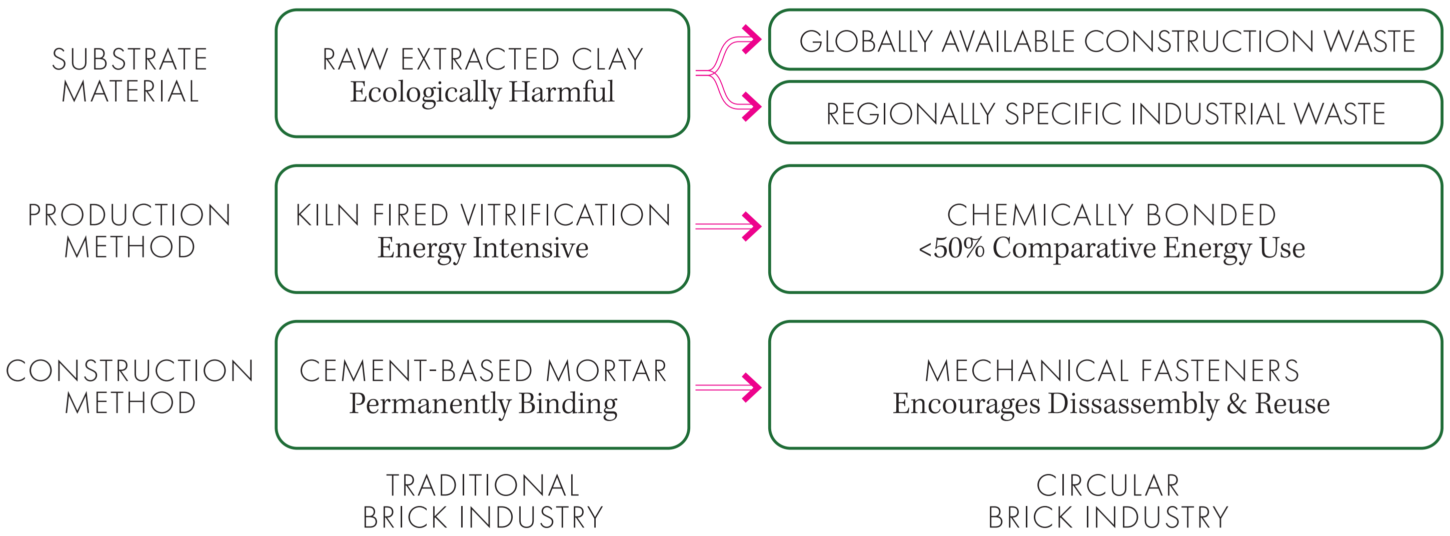


Figure 8.8 *Comparison of traditional brick material, production and construction practices with alternatives that would lead to a more circular brick industry (Diagram by author)*

8.2 ADAPTABLE CONSTRUCTION WASTE BRICK

In order to make brick a relevant material that responds to the environmental crises of the 21st century, it will require reconsideration of both its construction and production methods. These alternatives will need to maintain the positive attributes that have made it last for thousands of years, but also will need to address the negative characteristics that have made its current use unsustainable for present day challenges in the construction industry. The following experiment strives to combine industry advances that have been made individually within the construction and production methods of brick (see chapter 7), while also introducing a regional specificity to a material that has lost its connection to local environments in an increasingly globalized world.

Place Based Waste Methodology

The primary goals of this experiment were to examine the opportunities posed by material alternatives to traditional clay-based bricks, utilize a production alternative to the energy intensive firing process, and explore construction alternatives to cement-based mortars (Figure 8.8).

By finding alternatives to raw clay as the primary substrate material in bricks, much of the ecological degradation caused by mining (see Chapter 3) can be eliminated. The Anthropocene age is co-authored by centuries of over extraction, and it is imperative that the industry shifts away from the use of raw materials and gravitates towards repurposing the materials that are already available. For this reason, construction waste provides the ideal alternative to clay in the production of bricks. In addition, it further limits ecological damage by diverting construction waste bound for landfills. And if urban areas consolidate waste material for reuse in brick production, new production centers can sprout up alongside waste collection centers where they will have a steady stream of reusable material. Localized brick production also serves to limit the economic and environmental impacts of shipping heavy construction materials long distances. This is the current case with K-BRIQ in Edinburgh (see Chapter 7), and the same process can be expanded to cities across the globe.

Figure 8.9 *Examples of regionally expressive bricks. Chicago common brick (left) was originally viewed as a lower form of brick due to the poor quality river clay it was produced from, which resulted in a wide variety of colors and finishes (Photo courtesy of Katmerka Ramic). Milwaukee "Cream City" brick (right) is emblematic of the vast quantities of limestone in the region, which result in their bright blond finish that is now highly sought after (Photo courtesy of Susie Trexler). The unique characteristics of these bricks are now celebrated and potentially increase their chances for preservation or reuse.*

Utilizing construction waste also justifies the continued use of traditionally dimensioned bricks, which are oversized in their contemporary use as veneer walls. But when considering these bricks as repositories for construction waste, one can say that the larger size is a positive in that it extends the embodied energy carried by these repurposed materials. Just as Lundgaard & Tranberg and Petersen Tegl developed a methodology for the continued use of fired clay cladding in the contemporary construction industry (see Chapter 7), bricks produced from construction waste can challenge the notion that this is only a traditional material of the past.

While construction waste provides a promising alternative to clay, as exemplified by K-BRIQ and Waste Based Bricks (see Chapter 7), a further step can be taken by integrating industrial waste materials that express regionality. Historically, regionally harvested clay provided this same benefit, resulting in a myriad of brick finishes that were emblematic of a region's geology. As brick production has declined and clay excavation has been consolidated into a much smaller number of producers that often import clay from different regions, this regional specificity has been lost. But when considering local waste streams as a clay alternative, there are more opportunities to utilize locally produced materials that can create a new regional vernacular.

Brick construction has generally been an imported aesthetic in Seattle and lacks a personality that reflects the Pacific Northwest. For example, one of the most iconic brick landscapes in Seattle is the assembly of buildings at the University of Washington quad. While these are beloved buildings, they represent an imported collegiate Gothic aesthetic that borrows from European examples. The bricks are produced from local clay sources, but they are not as visually expressive as other domestic examples such as the finishes seen in Chicago common or Milwaukee "Cream City" bricks (Figure 8.9). Buildings constructed from these materials have now become associated with their respective cities by local residents, and in so doing they have a greater chance of being protected for many years by historic preservation groups. This study pursues a similar result by utilizing local waste materials in the production of alternative waste bricks, creating a new typology of "Place-Based-Waste Bricks" that can more adequately represent the Pacific Northwest while working within a circular framework of production and design. By utilizing a material that is more locally identifiable, these structures have the potential to be more associated with the region by Seattleites and also increase their chances of long-term protection and preservation.

Profile Design for Disassembly

The final hurdle addressed in this study is an alternative fastening method to traditional cement-based mortars. While lime mortars provide another option for disassembly, the expense of experienced installers and regulatory hurdles present immediate challenges that are difficult to overcome (see Chapter 7). Instead, the profile of the Place-Based-Waste bricks is designed to work with a mechanical fastening system in order to maximize adaptability and encourage disassembly and reuse. The form was inspired by Wienerberger's ClickBrick product, which uses small corrugated metal fasteners to horizontally connect bricks along a single wythe (Figure 7.9 & Figure 7.10). Six indentations in the top plane of the brick provide space for masonry anchors to fasten the wall back to a monolithic or vertical stud-based structural wall (Figure 8.10). All of the corrugated fasteners are set in thin channels that run side to side along the top and bottom faces of the bricks. These fasteners can be installed simply with a tap of a rubber mallet, which embeds the fastener into the brick to fasten the units together horizontally and tie it to the row of bricks above by embedding into the channel cut into the bottom face (Figure 8.11). A final indentation along the top of the exposed stretcher face of the brick is an aesthetic choice, as it creates a shadow line that references a traditional mortar joint. Without this gap the bricks would appear as a monolithic mass as opposed to individual units. These added details in the profile require a pressed production method, and would not be feasible via extrusion. These place-based-waste bricks are a wider format (11 ⅝" wide) than standard bricks (7 ⅝" wide) in order to maximize the amount of waste material in each unit and to limit the number of fasteners while still working within a modular design grid.

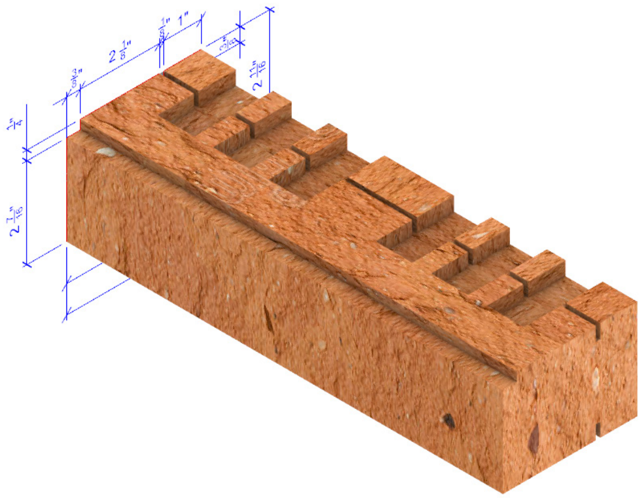


Figure 8.10 *Axonometric view of the individual brick unit profiles as they were being developed digitally (Image by author)*

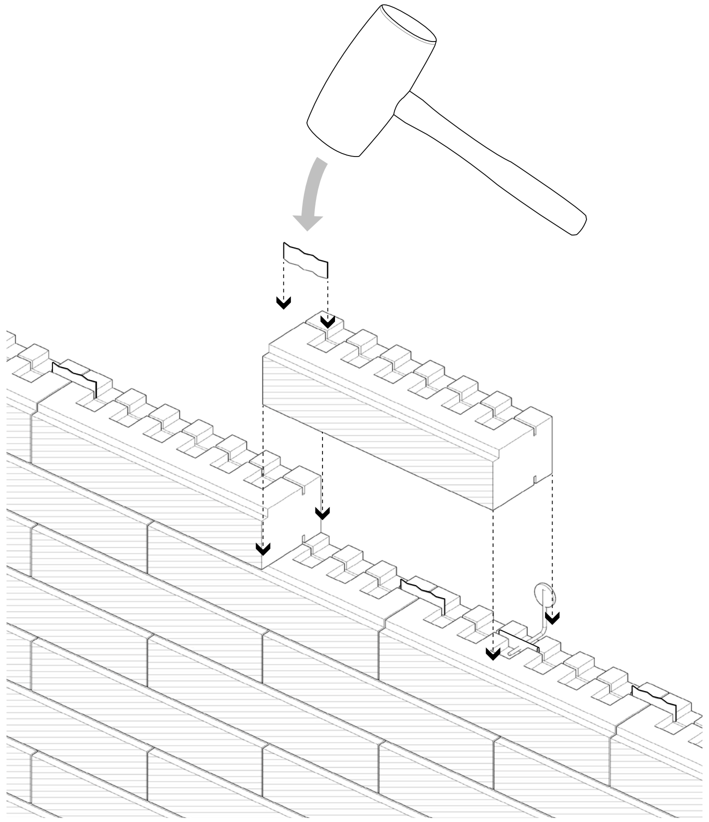


Figure 8.11 *Bricks are fastened together by corrugated metal strips without the need for mortar or special tools (Image by author)*

Material Selection

Materials were chosen that would take advantage of both universally and locally available waste streams. The first material, gypsum board from recycled drywall, was chosen primarily because of its widespread availability around the world (Figure 8.12, Figure 8.26, and Figure 8.27). In the Seattle area, roughly 15% of the drywall that arrives on a construction site becomes unusable off-cuts and is discarded as waste (Gypsum to Gypsum 2021). This is clean gypsum material that has not been exposed to paint or other hazardous materials, making it an ideal material for repurposing. Gypsum is also very similar to plaster of Paris and has natural binding properties when exposed to water. These binding properties can aid with the production of a non-fired brick, as it has proven to be a viable clay alternative in the commercially available K-BRIQ by Kenotech (Chapter 7). The Seattle startup company Gypsum to Gypsum has begun gathering this castoff material on construction sites for repurposing, providing an existing source of material for future brick production (Figure 8.14).

As a counterpoint to the ubiquity of gypsum, oyster shells were selected as a local waste stream that is emblematic of the Pacific Northwest coast (Figure 8.13, Figure 8.28 and Figure 8.29). Oyster shells are familiar with local residents, both as an aquatic farming industry along the coast and as a frequently served appetizer in restaurants. They are also highly visible along the Pacific coast of the Olympic Peninsula, where they are gathered in massive piles visible along the roadway (Figure 8.29). These collected shells are primarily used in specialty applications as a landscape aggregate or bocce court surfaces. The variations of color and subtle sheen provide opportunities for unique expression in the brick surface.

In order to develop an alternative to kiln fired brick, a binding material would have to be incorporated into the substrate mixture that would complement the gypsum in creating a strong and

Figure 8.12 *Recycled and crushed drywall (Photo by author)*

Figure 8.13 *Oyster shells drying after being scrubbed free of organic particles (Photo by author)*

durable product that could behave similarly to vitrified clay. Hydraulic lime was experimented with and proved to create adequate results. While hydraulic lime is also created via a firing process, it requires temperatures of 800 degrees C rather than 1200 degrees C required by brick and 1500 degrees C required by cement. And since it represents a smaller percentage of the overall substrate mix, it does not leave as much of a carbon footprint as the other two firing/binding methods. Another appealing factor of hydraulic lime is that it slowly reabsorbs the carbon emitted during its production process over its operable lifespan. This sponge-like reabsorption of carbon from the atmosphere increases the strength of the material over time and also helps to self-heal cracks that inevitably occur. And finally, hydraulic lime can be produced by heating oyster shells, which have very similar characteristics to limestone used to produce industrially produced lime. However, this study utilized a pre-manufactured hydraulic lime mixture in order to limit the variables and maximize quality control between test mixtures.

While the majority of the test samples consisted of gypsum and oyster shells, two additional waste additives were tested to consider their impact on the bricks. The first was powdered clay, which is a residual material found in brick production and recycling facilities. The team at Gypsum to Gypsum noted that gypsum particles bind with the clay in compacted soils, which is part of the reason it is a helpful agricultural soil amendment. Visual tests in this study proved this to be true, as mixtures containing gypsum and clay created a stickier and more congealed substrate that reduced porosity and improved final brick quality. The clay also added a subtle color variation to the mixture, producing an earthy tone.

The second additive tested was rubber powder from recycled tires. Interest in this material was sparked by the water resistant qualities of rubber and the great availability of tires from the automobile industry. This was only used in small quantities, and as with the clay, it proved to increase porosity and provide amenable color variation within the brick mixtures.

Production Process

The production process began with the procurement and preparation of the materials noted above. Oyster shells were provided by a local restaurant, and were later cleaned and crushed by hand into a variety of aggregate sizes. Premanufactured oyster flour was purchased to provide the smallest aggregate, which could not be produced with available methods. Recycled drywall was donated by the Gypsum to Gypsum (Figure 8.14). This material was sifted through screens to remove larger particles with facing paper bound to the gypsum. Hydraulic lime, powdered clay, sand, and powdered rubber were purchased from retailers.

A wooden mold was constructed to produce a series of 4"(W) x 4"(L) x 2.5"(H) samples that would test a series of 12 different mixtures before proceeding to full-scale mockups (Figure 8.16). The substrates were mixed with water and hand-tamped into the wooden molds, where they were left for three days prior to removal. The cured small scale mockups revealed that larger oyster aggregate sizes were not acceptable, as they created weak points at the corners and resulted in large cracks. They also revealed that high proportions of sand led to structural failures. Based on these results, three mixtures were selected to be scaled up to the full-size brick molds. The mixtures were as follows:

Mixture 1:
1 part lime, 1 part gypsum, 1 part oyster shells

Mixture 2:
1 part lime, 1 part clay, 2 parts gypsum, 2 parts oyster shells

Mixture 3:
1 part lime, 1 part rubber, 2 parts gypsum, 2 parts oyster shells

A larger wooden mold was created for the full scale bricks, and this time additional MDF elements were fastened inside the molds to produce the digitally designed “6 finger” profile that would accept the mechanical fasteners and masonry tie-backs (Figure 8.17). Due to the additional corners created by these profiles, Murphy’s Oil Soap was applied to the interior of the mold with the intent of creating an easier release after the substrates cured. Substrates were again mixed with water and hand tamped into the molds, where they were allowed to rest for 3 days (Figure 8.17). As they sat in the molds, they were occasionally misted with water in order to accelerate the carbonization process that was hardening the mixtures. Once the bricks were released from their molds, they were allowed to sit another two days adjacent to a humidifier. The final stage of production was to cut the side to side channel through the top and bottom face of the bricks. This was accomplished by placing the bricks back into their molds and cutting them against a jig with a circular saw fitted with a masonry blade (Figure 8.20).

Figure 8.14 *Drywall being ground down into an aggregate size at Gypsum to Gypsum’s recycling center in the South Park neighborhood of Seattle (Photo by author)*

Preparing Substrate

Oyster shells were first cleaned by hand to remove organic residue, then left to air dry. They were crushed using a kettlebell, then shaken through two sieves in order to produce multiple aggregate sizes, which is common practice in traditional brick manufacturing. Oyster shell flour was purchased from an oyster farm in the Pacific Northwest, as this finer aggregate size was not feasible to recreate with available methods. The recycled drywall was also shaken through a sieve to remove larger remnants of drywall paper adhered to the gypsum.

Figure 8.15 *Preparing substrate (Photo by author)*

Small Scale Samples

12 different material mixtures were tested in order to judge their efficacy prior to scaling up to full size bricks. They contained various ratios of hydrated lime, gypsum, crushed oyster shells, sand, rubber powder, and clay, which were hand mixed with water to create a slurry. The mixtures were hand-tamped into wooden molds to create 4"(W) x 4"(D) x 2.5" (H) blocks. The mixtures were left outdoors in mostly sunny conditions for three days before they were released from their molds. Larger aggregates and sand were determined to be ineffective.

Figure 8.16 *Small scale samples (Photo by author)*

Full Size Brick Molds

Full scale brick molds were built with wood, and MDF details were included to create the indentations for the mechanical fasteners. These bricks were "Norman" dimensions - 11 5/8"(W) x 3 5/8" (D) x 2 1/4" (H). This is wider than standard bricks in order to maximize waste material and limit installation cost. Murphy's Oil Soap was coated on the interior of the mold to prevent the mixture from adhering to the wood and MDF. Three mixtures were selected from the small scale sample tests. The mixtures were hand-tamped into the molds.

Figure 8.17 *Full size brick molds (Photo by author)*

Removing Bricks from Molds

The full scale bricks were left to sit in the molds for three days in mostly sunny conditions. They were misted twice per day with a light coating of water over a suspended cheese cloth. This additional moisture was intended to create a more humid environment that would accelerate the carbonization process of the hydrated lime binder.

Figure 8.18 *Removing bricks from molds (Photo by author)*

Bricks Rotated and Left to Dry

After three days the bricks were removed from their molds and flipped upside down in order to create more even exposure on all sides of the bricks. They were left upside down for one additional day. There was noticeable curvature in the bottom of the bricks, indicating uneven carbonization.

Figure 8.19 *Bricks rotated and left to dry (Photo by author)*

Final Channel Cuts

The molds were repurposed as a jig for cutting the final side to side channels into the top and bottom faces of the brick. These cuts were made with a circular saw fitted with a masonry blade.

Figure 8.20 *Final channel cuts (Photo by author)*

Manufacturing Metal Fasteners

Mechanical fasteners were produced from 20 gauge galvanized steel strips, which were purchased with a pre-manufactured width of 1 1/4”. The steel was bent into a corrugated pattern with a press brake. These corrugations were intended to increase adhesion within the channels of the bricks. Holes were punched and threaded in the corrugated strips to accept the masonry anchors.

Figure 8.21 *Manufacturing fasteners (Photo by author)*

Final Resting

Prior to testing the bricks with the corrugated fasteners, the completed bricks were left to rest an additional two days adjacent to a humidifier to increase moisture in the air and accelerate the carbonization process.

Figure 8.22 *Final resting (Photo by author)*

Figure 8.23 *Completed "place-based-waste" brick mockups (Photo by Jeremy McGlone)*

Figure 8.24 *Masonry ties are fastened to the bricks through threaded holes in corrugated mechanical fasteners. The fastener location can be adjusted to any of the six indentations in order to align with wall stud locations in the structural backing wall (Photo by Jeremy McGlone)*

Figure 8.25 *The addition of small amounts of rubber powder (top), clay (middle), or no additives (bottom) produced a range of earth tones in the completed bricks. (Photo by Jeremy McGlone)*

Findings

Results from the experiment were generally successful and encouraging enough to continue testing and refining the waste material mixtures and production methods. All of the bricks emerged from their molds fully intact, and six days after their initial mixing they proved to be quite solid with the ability to accept the mechanical fasteners. Additional controlled quantitative testing is required to determine their precise compressive strength. This testing would ideally occur at different time intervals after mixing in order to determine the ideal setting time.

Two primary issues during the brick production phase produced the most impactful errors. First, the bricks dried unevenly because they were left in their molds for the first three days after being poured. This resulted in noticeable bending along the bottom face of the bricks, as the moisture content along the center of the bricks was released at a different rate from the edges. Further studies should consider removing the molds as soon as possible to improve how evenly air is exposed to the mixture.

Second, some of the bricks exhibited significant cracking along their top face with the six masonry anchor indentations. These indentations proved to be too much detail for this type of waste material mixture, particularly when the material is hand-pressed into molds. However, the mixtures with the clay additives performed best in these areas, indicating that the minuscule clay particle sizes improved adhesion around these details. Further studies should consider clay additive mixes, smoother alternatives to wood as a mold material, and a hydraulically pressed production method. The hydraulic pressing in particular could yield improved results by reducing air bubbles, improving compressive strength, and permitting tighter detailing around the masonry anchor indentations.

Mechanical fasteners were successfully installed into these brick mockups, holding together the bricks with adequate strength to stack them horizontally. However, it was noticed that the slight bending from the uneven drying of the bricks made it difficult to evenly stack each course. Due to the irregular nature of brickmaking, these gaps would likely occur even without this bending. Future testing should consider methods for planing the top and bottom faces of the completed bricks to ensure even runs of brick courses. This is similar to the methods Wienerberger uses for dry stack ClickBricks. Additionally, the corrugated metal fasteners could be made more consistently and faster with an alternative to a hand-operated press brake.

On an aesthetic level, the bricks produced a pleasing mixture of earthy tones that resulted from the materials incorporated into the mixtures. The lighter tones created by the primary materials, gypsum and brick, offer a line of color finishes that often correlate with a price premium in the traditional fired clay brick industry. The continuous side to side indentation along the front stretcher face of the bricks successfully replicated the shadow line of a traditional mortar joint, and also helped disguise the gaps between the uneven top and bottom faces of the bricks. Subtle cracking in the face of the clay bricks produced an uneven texture that alluded to the hand made rather than machine extruded production process, which is considered a premium in European markets.

There were also some aesthetic drawbacks revealed during production. Due to the limitations in aggregate size that were discovered in the small scale sample mockups, it is difficult for a viewer to understand which waste materials are included in the bricks. This is the same issue seen in K-BRIQs, which have a similar waste material makeup that does not express itself visually. In order to combat this, future research could explore the use of unfired glazes or sprays applied after the bricks emerge from their molds. Saw cut or sanded faces could also be incorporated into the production process to better expose waste aggregates while enforcing more homogeneous dimensions.

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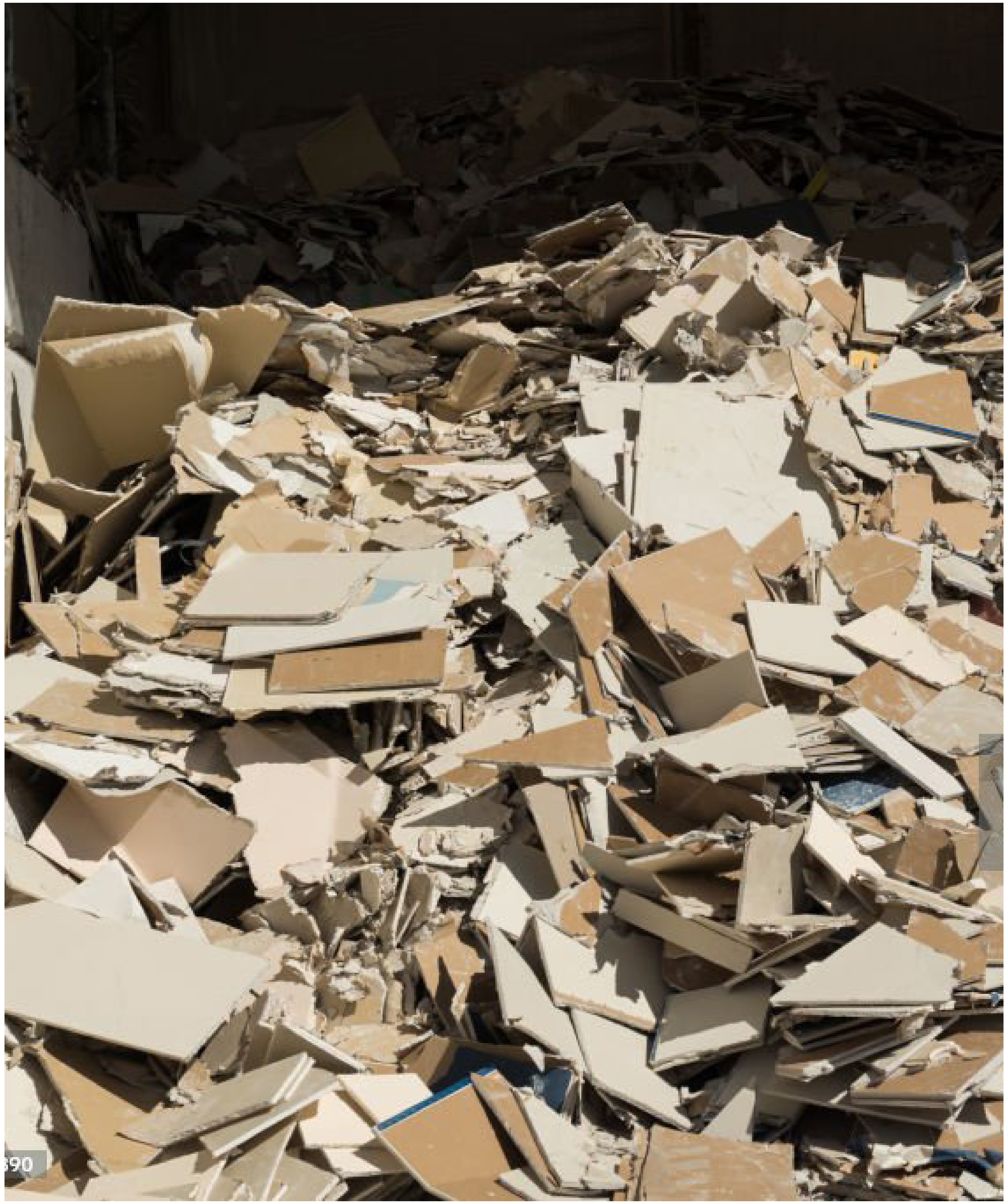

Figure 8.27 *As much as 20% of drywall that arrives on site is discarded to landfills as off-cut material (Photo courtesy of AscentXMedia)*

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Chapter 9

Conclusion

Brick has been a reflection of the natural, cultural, and constructed environment for thousands of years. Produced from locally extracted earth, water and fire, sewn together by skilled hands representing cultures across the world, and standing for generations as monuments that continue to shape urban lives. But this connection has diminished as global reach has expanded, diluting the threads connecting these realms. This untangling has coincided with an environmental crisis that is tied to centuries of overindulgences in the construction industry. However, with some irony, this simple material that rose alongside humanity's earliest civilizations is now revealing itself to be a contemporary response to natural resource depletion, while also holding the potential to mirror our local environment.

The inherent characteristics of brick are aligned with the circular economic principles that offer a more sustainable future for the built environment. But an analysis of the full life cycle of brick, from excavation to disposal, reveals several key moments that are limiting the sustainable attributes of the material. This project has explored each of these life cycle impacts and devised a coordinated methodology for maximizing brick's circular potential.

In order to better understand the full life cycle impacts of the brick, the project began with a review of the past and present practices of the industry. First, a historical review focused on the factors that led to the material's 20th century proliferation and 21st century decline in the Pacific Northwest, revealing the number of brick masonry buildings at risk of demolition in the near future. Next, the destructive impact of clay mining in the Duwamish River Valley revealed the threat these abandoned mines still pose to present day soil, wildlife, and human health. The review concluded with an exploration of the most common brick production and construction methods used in the contemporary United States, which is responsible for high energy demands and limited opportunities to disassemble and repurpose this highly durable and adaptable material.

A life cycle analysis followed, revealing specific opportunities within the preservation, excavation, production and construction practices of the industry that have the potential to improve the circular characteristics of the material. The proposed alterations were further informed by successful case studies that independently tackle these issues.

These case studies proved there is great work being performed in the US and internationally to improve each of these four life cycle stages in the brick industry. But this project aims to highlight solutions that perform across the boundaries of these four categories, which can result in exponentially greater impacts on the industry rather than solving them independently. Life cycle thinking allows us to understand the full value of brick, a simple material that when considered within a circular framework has substantial opportunity to address the issues facing the 21st century. In the face of many over-designed solutions that are being proposed within a circular economy, this project suggests it may be better to revisit an updated version of our oldest building material.

Rather than reinvent the wheel, reuse the brick.

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Chapter 9: Conclusion

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