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Digital Fabrication for Contemporary Material Specificity

Pattullo, Hayden

UNIVERSITY OF CALGARY

Digital Fabrication for Contemporary Material Specificity

by

Hayden Pattullo

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Abstract

The modernist model of "logical positivism" that emerged in the early-20th century Modernist movement placed the onus of design squarely within the material world. This movement attempted to replace the immaterial "metaphysical" approach to design and material with physically-provable absolute concepts of materiality. However, this model failed to recognize that the value and use life of modern material is highly contingent on distributed and imperceptible immaterial systems such as supply chains and reverse logistics that function beyond immediate scales of space and time (scales that are classically the territory single buildings and products). Approaching the design of buildings and objects through this constrained scalar lens has produced a significant amount of waste via inefficient object lives and perpetuated the logical positivist model of design through the wide misuse of current digital design tools.

Contemporary notions of material specificity, such as DeLanda's "possibility space" and McDonough and Braungart's Circular Economy, attempt to reject logical positivism by identifying the contingent factors, or "events," across a material's life that must be designed for, such as its flexibility between uses and adaptability within the supply chain. Through a series of literature reviews, case study analyses, and experiments, this thesis will demonstrate the waste problems associated with logical positivism in modern design, describe the Circular Economy as a new form of event-scale for the design of materials, and posit how contemporary digital tools may be instrumentalized for material design at these new event-scales. Ultimately, this work constructs a new conceptual framework of event-scale thinking for material, which promotes different and less wasteful applications of digital tools in design and production.

Keywords: Digital fabrication, architectural design, additive manufacturing, material optimization, circular economy

Preface

The following thesis aims to establish a new conceptual basis upon which to focus the contemporary use and problem spaces of digital design tools in architecture, in order to address modern problems of material and object durability. This thesis originally stemmed from an ambition to explore the wasteful use of plastic in modern architecture, however the findings from this initial exploration provided motivation to explore the broader wasteful material models proliferated by modernist design theory. In pursuit of the aforementioned goal, this thesis is divided into three primary sections (chapter 2, 3, and 4), each with distinct (yet interdependent) goals and methods.

Chapter 2 aims to demonstrate the existence of broader cultural models for material and object value and demonstrate their incompatibility with biological logical positivist models of value perpetuated by modernist theory. It does this firstly through a literature review into modern streams of physical waste in order to establish the key problem and its link to modernist design theory. Secondly, this chapter conducts a literature review to compare the concepts of cultural/dynamic material value and of biological essentialist material value. Lastly, the chapter performs a pair of historic case study analyses into the value problems that exist around high-performing modern materials and construction methods in order to demonstrate the strength of non-essentialist cultural value models to dictate physical material value and lifespans.

Chapter 3 aims to establish the concepts of the event-scale and the Circular Economy as new critical territories through which contemporary design can address material waste and specificity. This involves a brief historical analysis into the postmodernist critique of modernism and the movement's concept of the "design-event" pioneered by Bernard Tschumi, then transitions into a literature review of the Circular Economy concept and a series of case study analyses on the use of design to address broader-scale contemporary material problems over time.

Chapter 4 concludes the findings from the previous three chapters with a series of experiments that explore how digital design techniques can transform existing typologies of building material to meet new levels of specificity and new Circular Economic design metrics. This firstly involves a literature review into the new material metrics introduced by the Circular Economy and reverse logistics, such as material reuse supply chain consistency and material embodied energy. Secondly, this chapter identifies case studies in digital fabrication for Circular material efficiency, and thirdly uses these case studies to develop a series of digital techniques and physical experiments for optimizing material embodied energy and responding to supply chain considerations.

All diagrams contained herein from the 2019 "Designing Out Waste" publication (Guldager-Jensen et al, 2019) are used with the express permission of all co-authors. All additional diagrams are reinterpreted from their original sources, or original unless otherwise noted.

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Finally, I would like to extend my utmost gratitude to my family, friends, and colleagues at the Laboratory for Integrative Design. None of this research, nor the faculty that enabled it, would have been possible without the leadership and tireless work of Jason Johnson and Guy Gardner. And ultimately, my entire architectural education would never have transpired without the unconditional support of my parents and my best friend Alexis to guide me along the way.

Dedication

For my best friend, Alexis Handford.

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Glossary of Terms

Additive Manufacturing	Additive manufacturing is another term for the process widely known as 3D printing, in which liquid material such as plastic or concrete is deposited in layers and hardened to create solid form.
Biological Material Value	Value models for physical material that are based on a material's essential and intrinsic qualities that can be observed and felt by humans. This can include a material's physical strength, density, transparency, or other. Also referred to as essentialist material value or essentialist materialism.
Building Information Modeling (BIM)	Building Information Modeling creates a virtual 3d building model with a series of physical and functional characteristics, in order for various professions to design and model the building in unison
Circular Economy	A system that attempts to minimize waste and maximize resource use by establishing closed object and material reuse loops; the opposite of the conventional linear economic model in which resources are extracted and transformed into products, which are used and then discarded.
Cultural Material Value	Value models for physical material that are based on their extrinsic interaction with subjective and contextually specific human socialization. This could include the perception of a material's exoticness, rarity, beauty, or other subjective factors, based on the context in which a material is used.
Digital Fabrication	Digital fabrication refers to processes of physical production (creating buildings or products) that involve direct translation of commands from digital space to physical material. This includes 3d printing, CNC milling, laser cutting, and robotic fabrication.
Logical Positivism	A concept that attempted to bridge artistic and scientific disciplines in the early-20th century by establishing common rational foundations for all processes. These foundations decreed that all design and philosophical thinking would be built entirely on scientifically-provable concepts and that architecture and materiality

	could therefore be distilled down to fundamental and reliable objective knowledge.
Material Specificity	Material specificity describes how physical materials and objects (their qualities and value for example) are filtered through human subjective perception, and therefore the function of these materials and objects is inherently based on a variety of both objective material and immaterial contexts across space and time.
Material	In the context of this paper, material is referred to as the raw physical resource (down to the molecular level) that is used to produce an object. The use value of the material is its use in an object, however by merit of being physical, it has inherent energy and use potential.
Object	In the context of this paper, an object is defined as any single assemblage (whether chemical, physical, or otherwise) of materials designed and produced for consumer use. This can include consumer products, building components, and whole buildings themselves.
Parametricism	Parametricism is a style of contemporary architecture in which digital parameter-based tools such as Grasshopper are used to translate the complexity of life and processes in the current network society into physical architecture
Possibility Space	The possibility space is a term used by Manuel DeLanda to describe all qualitative dimensions and their structure of influence in affecting material form. For example, the possibility space of water could be seen as a three-dimensional surface describing the relationships between pressure, volume, and temperature and the three potential states of water.
Reverse Logistics	The reverse flows of material and labour from buildings and consumer products for the purposes of recycling and repurposing. The opposite of logistics, which sends material and labour into the production of buildings and products.

Epigraph

"We live in a world populated by structures – a complex mixture of geological, biological, social, and linguistic constructions that are nothing but accumulations of materials shaped and hardened by history"

- Manuel DeLanda

Chapter 1
Introduction

Perhaps the most resilient legacy of the 20th-century modernist movement is its overarching materialist philosophy, which still strongly influences the design of our built world today. This was a material philosophy constructed around the concept of "logical positivism," or the idea that all philosophical and design thinking should be built entirely on scientifically-provable concepts and thereby banish the "decorative, mystical, and metaphysical" (Galison, 1990 p. 710). The ambition of the logical positivism movement was primarily to politically bridge common ground between the early-20th fields of arts and sciences through common rational foundations, with a secondary motivation to de-politicize these fields by removing any sense of nationalism and historicism (Galison, 1990). By the nature of this ambition and of the limited design and analytic tools available in the era of its inception, a central focus of modernism was its use of objective material realities to re-shape the political, social, and economic landscape (referred to as "the spirit of modern times"). In the 1920s, Bauhaus founder Otto Neurath declared that anybody seeking to be liberated from the past "will seize upon the formation of the new form of life as a technical advancement" (Galison, 1990, p. 716). In many ways, this ambition succeeded, and the broad disciplinary concern in modernism led to its influence permeating a multiplicity of fields in the mid-20th century, including politics, design, philosophy, art, and more.

However, the broad reach of logical positivism also conveyed an underlying belief that material form had the power to circumvent and/or reshape immaterial systems to its will, which has produced a wide-ranging set of consequences that have been magnified by contemporary global issues. Early ambitions of modernism to improve the material needs of the working class by providing mass accommodation (DeLanda, 2008, p. 160) were ultimately revealed by American public housing projects to be woefully incapable of alleviating poverty and producing the idealist socioeconomic conditions they promised through material form alone (Jencks, 1977, p. 9). Furthermore, the planned obsolescence of 20th-century consumer objects succeeded in initially re-shaping the economy around boundless material consumption, however, it eventually became a massive economic and environmental burden by its associated waste production (Maycroft, 2009).

In addition to these consequences, the implication that materiality could be composed of linear and absolute physical properties has and continues to significantly hinder our ability to consider and truly design for scales beyond immediate physical form of buildings and products. The lingering modernist approach to object design and durability can be seen to draw from Vitruvian and Newtonian-esque concepts of materiality that make absolute material claims, such as how the

physical strength of a material can enable it to survive "forever" (Touw, 2016, p. 4). A similar ethos can be observed in the design of modern buildings and products of the late 20th and early 21st century that seemingly plan to exist forever with little contingency. A building's structural systems are designed to last hundreds of years (O'Connor 2004) through their non-reversible connections and high amounts of material consumption, however these systems are not designed to allow the building to adapt as necessary to meet changing economic and cultural conditions throughout the building's life that are more likely to affect its lifespan than its structural strength is. This is also reflected in typical financial models for buildings, which primarily consider the building's return at the scale of its financing period, not the scale of its physical potential use life, or the use lives of its respective materials, which often have longer use value beyond the building itself (Guldager-Jensen et al, 2019)

This ethos continues to perpetuate itself through the application of contemporary digital design tools as well, such as Building Information Modeling and parametric design. Modern Building Information Modeling (BIM) is a virtual 3d building model that typically contains information about its materials, operation, and construction over a limited span of its lifetime (usually during which it is built and operates over its financing period), rather than taking advantage of tis potential to virtualize a building's long-term maintenance and upgrading, its post-occupancy removal challenges, and/or subsequent handling of its individual materials. Furthermore, the applications of parametricism, or parameter-based digital design, have also advanced little beyond the physical building-scale architectural concerns of the pre-digital design age, where the scales of physical form and its immediate production still reign supreme. The use of these tools to address broader scales of design is becoming not only possible, but necessary, given the complexity of these problems. This is evidenced through claims such as Schumacher's, that parametricism "is the only architectural style that can take full advantage of the computational revolution" (2016, p. 10). As demonstrated by modern building lives, any design approaches that continue to linger in the perceptible short-term scale of the physical building are incapable of addressing the broader scales of material, space, and time that have increasingly significant influence over our use of resources, labour, and money.

The linear essentialist approaches to materiality in design (which linearly relate physical properties with material value and longevity) stand in stark contrast with contemporary models of materiality of philosophers such as DeLanda (2008) and Meillassoux (2008), who assert that each physical material is defined by a high degree of specificity via events and value models across its entire life, and that

no property of a material is truly absolute (physical strength or presence does not guarantee longevity, or even value). Perceiving and valuating a physical material through a purely objective lens (the "world in itself") is impossible through human subjective perception, therefore it is through a mixture of physical, cultural, economic, and other contexts that material gains and loses value and meaning (Sadalla and Sheets 1993). Links between physical material and its use life and value have progressively demonstrated the flaws of essentialist materialism, evidenced by modern phenomena such as buildings and products representing negative value to their owners before the end of their useful physical lives. This reliance on essentialist physical value models for material continues to produce a significant amount of waste from the production of built objects that are not designed to be resilient towards broader imperceptible scales of space and time.

Postmodern and contemporary models have rejected the modernist primacy of physical form in favor of specificity towards contextual "events" that happen across broader scales of space, time, and economics in each material's life. One key emergent model in this trajectory is the notion of the Circular Economy, which seeks to maximize the use life of physical material by mapping its entire life, events that will affect this life, and opportunities for its reuse in various forms. This concept centers largely around notions such as "reverse logistics," which attempt to optimize the amount of additional energy and money that are put into end-of-life objects and materials in order to recover, process, and reuse them at various scales. This approach has two main implications. Firstly, in unison with contemporary digital tools to quantify embodied energy, the circular approach removes the need for material to retain consistent physical form in order to preserve its usefulness (meaning that sustainability becomes a purely energetic metric wherein materials can change form to retain use and value). Secondly, the Circular Economy provides new design criteria at the material level that have the potential to bridge feedback between beginning and end-of-life object design. This has birthed design approaches such as "designing for recycling," which places performance of a material's circular reuse closer to par with the physical function of the respective object it comprises. Since modern design objects such as buildings and consumer products have typically prioritized the short-term performance metrics of the object, a shift to prioritize the long-term lives of component materials has the potential to question how common object typologies and design models of the 20th century may change.

Contemporary digital design and fabrication strategies have more generally been instrumentalized for non-circular practices that prioritize physical formalism and short-term economic return at the

object scale, however the concepts of specificity in material reuse present significant opportunities to pivot digital techniques towards circular applications and new design problems. As opposed to many existing contemporary applications of digital design, the concepts of material specificity and the possibility space are proposed as new techniques to leverage design control and distributed thinking for the purposes of material circularity. The use of techniques such as additive manufacturing stand to address the essentialist assumptions of modernism by producing materials that maintain use through their physical specificity and resilience to changing social, cultural, and other broad-scale events throughout their life.

The explorations in this work question material standardization by demonstrating how digitally-facilitated control and specificity over material production may allow materials to better address broader-scale metrics of circular design, such as embodied energy and supply chain availability. This thesis therefore aims to discuss how the Circular Economy represents a new event-scale for contemporary design, as well as explore how emerging digital fabrication strategies may facilitate more effective material strategies towards these ends. This exploration will begin with an analysis of 20th century material value models to demonstrate the origin and effects of essentialist logical positivism on design, which will subsequently be used to critique new scales of event-based design models such as the Circular Economy. The critique of these design approaches will be utilized to develop a series of experiments in digital material fabrication that target new criteria such as embodied energy optimization and supply chain responsiveness in the design of architectural objects. Ultimately, this approach will utilize digital design and fabrication to demonstrate a greater level of responsiveness and integration with circular design material goals and establish a new conceptual model for circular design as a new design event.

Chapter 2
Linear and Distributed Models of Object Durability

In a 2004 survey by O'Connor of 227 North American buildings demolished between 2000 and 2003, the majority of non-residential (predominantly steel and concrete structure) buildings were under 50 years old (figure 1) (O'Connor, 2004), representing a significant shortfall from the designed physical service lives of 75+ years for these structural systems (figure 1). This effect is mirrored in the United Kingdom, where research shows the majority of buildings demolished in the late-1990s were between 11 and 32 years old, despite that housing construction in the UK peaked prior to the late 1960s (DETR and DTZ Pieda Consulting, 2000) (figure 2). In examining the data, O'Connor notes that buildings with more physically durable steel and concrete structures were found to have shorter actual service lives than the buildings with wood structures (figure 1) (O'Connor 2004). 60% of the wood structure buildings surveyed were older than 51 years upon demolition, compared to under 35% for the concrete buildings and 20% for steel buildings. Furthermore, the wood structure buildings were far more likely to live long enough that physical failure was their reason for demolition, where the top reason for demolishing the steel and concrete structures was that they were "no longer suitable for their intended purpose" (O'Connor, 2004, p. 3).

One key conclusion drawn from O'Connor's 2004 study is that there is a significant disparity between how long modern buildings *can* last and how long modern buildings *do* last, and that a building's typology has more correlation to its life expectancy than the building's material durability. The juxtaposition of longer potential physical durability (through material and technological advancements of the late-20th century) with shorter operational building durability invokes Meillassoux's (2008) concept of "hyper-chaos," in which the assumed absolutes of physical laws (or in this case architectural laws) are truly only contingent on a series of specific conditions to function. These studies on mid to late-20th century building lifespans suggest that architectural "absolutes" such as physical durability and quantitative performance (notions that architecture most commonly associates with physical material durability) often hold little correlation with the actual longevity of buildings and materials. This creates considerable problems for contemporary architecture, which

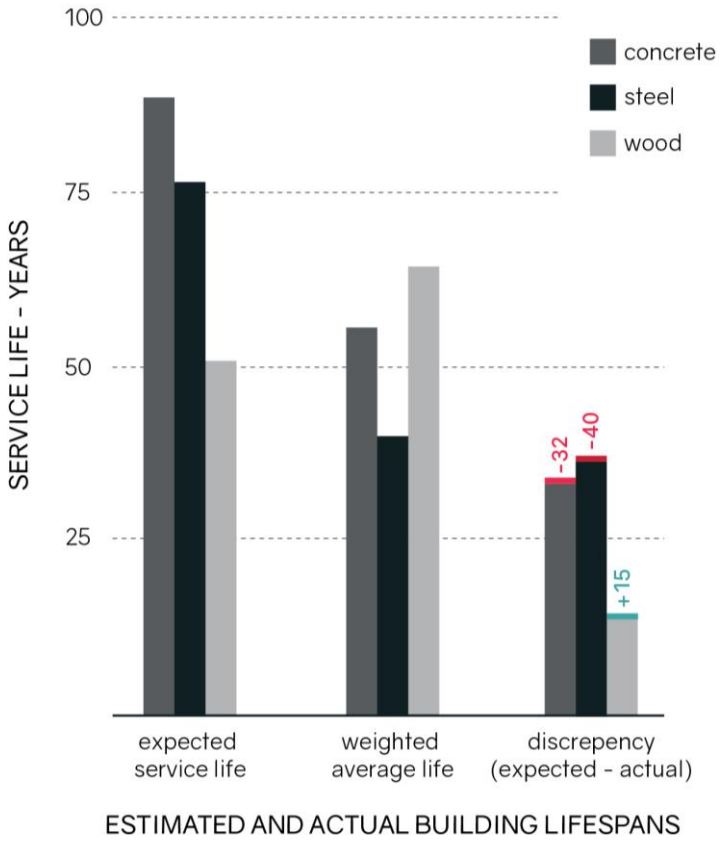


Figure 1: the expected service lives, actual surveyed service lives, and dicrepency of buildings by material (reinterpretation of a diagram by O'Connor, 2004)

Ford (1990 p. 3) claims still follows the lingering modernist paradigm of "the expression of permanence through solidity and mass."

This lingering use of one-dimensional essentialist (or intrinsic) material factors of physical longevity is significantly contributing to contemporary global problems of waste and pollution. The building industry today is responsible for up to 40% of material production globally, and approximately 35% of the world's physical waste (International Energy Agency, 2018), which contributes to accelerating worldwide resource scarcity. This is severely compounded by the fact that most buildings do not live to reach their designed physical potential (O'Connor 2004) and the rate of material reuse and recycling from building demolition is estimated at less than 55% (Tam, 2011). However, physical waste is only one of three major forms of waste produced by modern building lifespan models. Energy is also wasted through the production, transportation, installation, and disposal of materials that do not reach their full physical potential, as well as through the power sent to low-occupancy buildings that are no longer desirable in their respective market. Furthermore, built space (and the associated money to build and operate it) is wasted as it becomes prematurely-undesirable with few options for renovation or replacement.

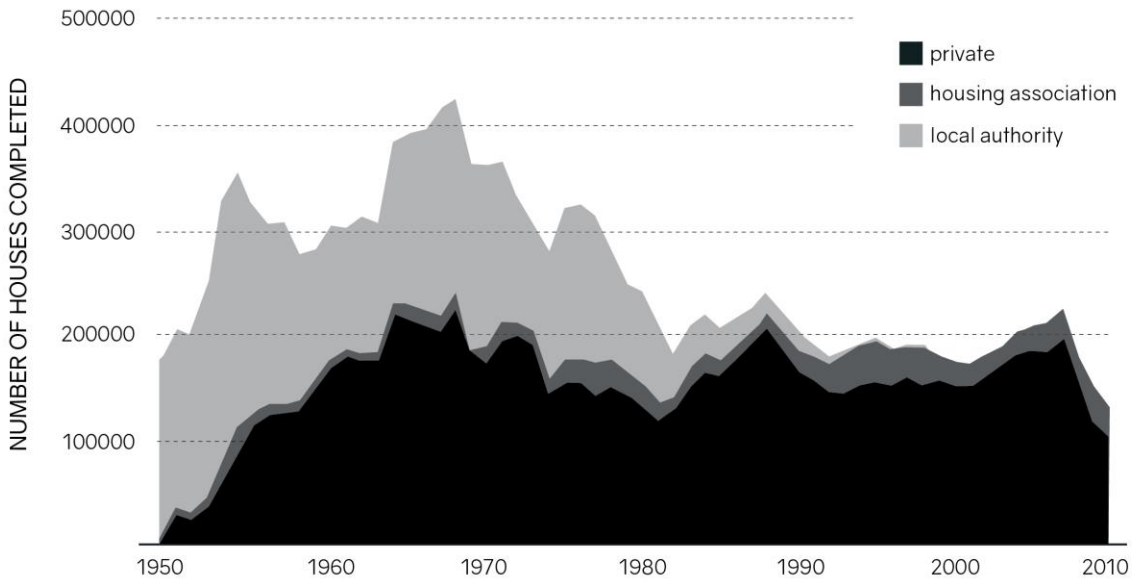


Figure 2: UK Residential Construction rates since 1950 (reinterpretation of a diagram by the Ministry of Housing, Communities, and Local Government, 2018)

Therefore, common linear essentialist models of materiality, such as the assumption that buildings will last longer if they are physically stronger and higher-performing when they are built, should be fundamentally questioned. These include models such as Vitruvian Firmitas (defined by Virtuvius as the physical strength of a building) and Newtonian materiality (which states a direct linear relationship between the use and value of a material and its inherent physical properties) that rely purely on the physical properties of materials to determine their value and durability. In their place, this chapter proposes new conceptual models of materiality that consider the contingency of physical value and longevity on dynamic cultural and economic factors. Notions such as Sadalla and Sheets' (1993) "cultural value" and DeLanda's (2015) material 'singularity" can be used to demonstrate the true nonlinearity of physical value and suggest alternative conceptual models to approach the design of durable materials and buildings.

Therefore, based on the revealed shortfalls of modern building lives and their associated waste, this chapter aims to critique lingering modern essentialist assumptions of architectural durability by analyzing how broader models of cultural and economic value interact to affect building and material lives. As Greg Lynn suggests in Bell's 2013 book on plastic in architecture, the modern preoccupation on physical and technical durability of materials may have inversely shortened their

lifespans by ignoring the multitude of other modes by which these materials gain and lose value (Lynn, 2013, p. 108). To explore this issue, this chapter identifies two scales of historical case study (building-scale, and material-scale) that strongly demonstrate the contingency of cultural value effects in determining the physical longevity of buildings and material. By examining the case studies of industrial prefabrication and plastic products in post-functionalist late century design, this work will demonstrate the inability of essentialist durability metrics to meet the dynamic factors that control material and architectural use lives, and subsequently suggest new ways of addressing durability in architecture.

2.1 Modern Forms of Architectural Waste

Incurred by factors such as increasing cultural change, technological progress, urban migration, and economic instability, building turnover in the late-20th century was occurring in a higher cyclical rate than ever before, based on studies such as O'Connor et al (2004), DETR and DTZ Pieda Consulting (2000), and Yashiro et al (1990). This presents a significant challenge, considering that most modern architecture is still designed and constructed according to traditional essentialist assumptions of Vitruvian "Firmitas," wherein the physical strength of materials has the highest perceived currency in determining their value and use life. Based on the aforementioned studies, and Touw's (2006) conclusion that disposable architecture has become the dominant urban development paradigm, the assumption that physically-strong buildings will last "as long as they can" produces a number of serious issues with waste in modern building development. Modern architectural waste can be roughly categorized into three categories of material waste, spatial/economic waste, and energetic waste.

Modern building material waste primarily stems from the way that buildings are constructed in relation to their use lives and material layers. As observed by Guldager-Jensen and Sommer (2016), the materials in most modern buildings are assembled in ways that assume the materials will be worthless once the buildings are demolished. This means connecting materials with non-reversible techniques (such as welding or casting), compositing materials that cannot be mechanically separated (such as laminating metals and plastics together) and using materials in damaging ways that prevent their potential maintenance and/or reuse. This means that when buildings are demolished before the useful physical lives of their materials are concluded, there is no opportunity to divert those materials into other uses and they are subsequently disposed of. Furthermore, these material

strategies also prevent buildings from easily reconfiguring to solve nonphysical issues such as market shifts, resulting in buildings with more rapid devaluation.

This devaluation is the key contributor to modern spatial/economic waste in building practices. As examined in Designing Out Waste (Guldager-Jensen et al, 2019, p. 32), markets with high economic volatility such as those in Calgary AB can see building occupancy rates as high as 26% and up during recessions, which often means older buildings from the 70s and 80s become mostly empty as demand lowers and newer space becomes cheaper (Figure 3). Due to the assumption of permanence in how these buildings were constructed, extensive renovation and demolition/reconstruction are incredibly costly and labor-intensive. Therefore, considering the options for owners of undertaking costly renovations to improve or repurpose buildings, or undertaking even more costly demolition and reconstruction, many owners opt to leave space empty and wait for the market to rebound. This not only creates significant financial losses for building owners who are forced to service empty space with no rental income, but also significant tax losses for municipalities as the property values of those buildings drop. In the previous three years of recession, empty office space in Calgary has resulted in the loss of over $600 million in rental income and over $12 billion in taxable building value (Guldager-Jensen et al, 2019, p. 33).

The energy that is wasted to service empty space is just one part of the significant energetic waste produced by shortened building use lives. A significant amount of energetic waste also results from the "Embodied Energy" of building materials that is wasted when they are prematurely discarded, where embodied energy is the total energy required for the extraction, processing, manufacturing, delivery, and eventual disposal of building materials (Guldager-Jensen et al 2019). As claimed by Adams, Connor, and Ochsendorf (2006, p. 205), the embodied energy of a building's materials can compose up to half of its total energetic footprint over a 50 year period (Cabeza et al, 2013, p.232), depending on the type of building and its operational efficiency. Our ability to quantify embodied energy over the full lifespan of materials through digital Life Cycle Analysis (LCA) tools has created strong incentivization to ensure materials live out their full physical potential. Premature disposal of materials with longer potential lives not only wastes the energy used to create those materials, but also wastes energy that is subsequently used to produce new material to replace them, rather than reusing the existing materials that still have remaining use value.

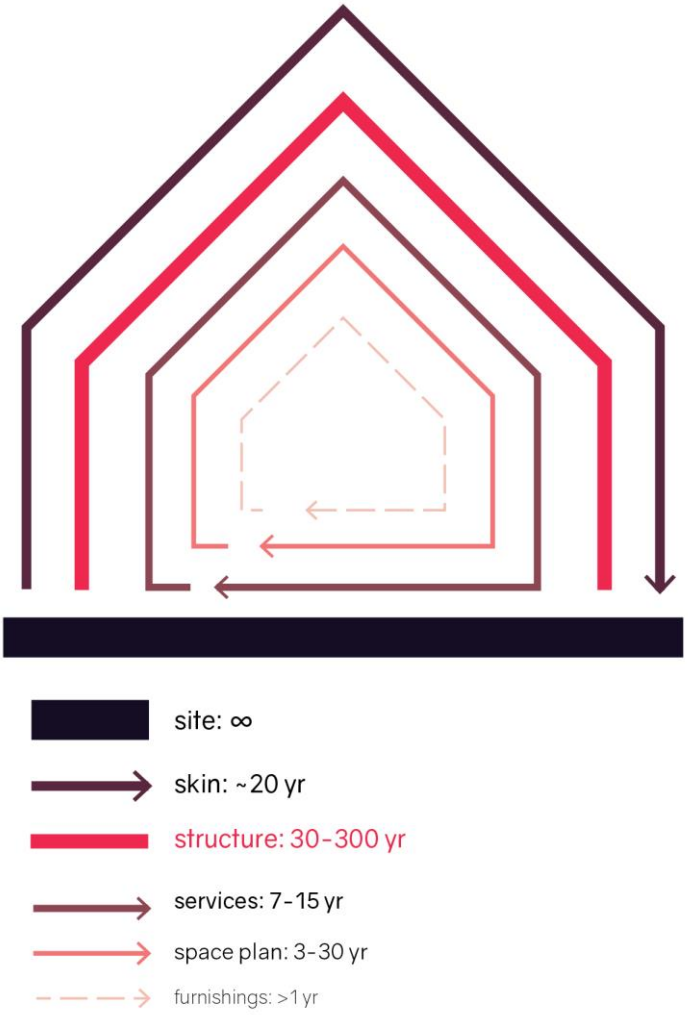


Figure 3: The layers of a building and their associated replacement intervals (reinterpretation of a diagram by Brand, 1995)

The interconnected relationships between material waste, energetic waste, spatial/economic waste, and Vitruvian-based building design models can be explained largely through Duffy's (1990) and Brand's (1995) building shearing layers problem. The concept of "shearing layers" first introduced by Duffy (1990) and popularized by Brand (1995) distinguishes six discrete physical layers of a building (site, structure, skin, services, space plan, and furnishings) that each have a different potential operational lifespan (figure 3). This concept explains how the physical elements of a building's structure, for example, comprise high-strength material that is capable of functioning up to 300 years for material such as concrete and steel. Inversely, interior space plans may require

replacement up to every three years, and furnishings may only last one day (Brand, 1995). This model suggests that, contrary to essentialist Vitruvian durability, a building's use life may only last as long as its shortest-lived non-replaceable layer, as the failure of any one layer can cause the building to rapidly lose value, tenants, and eventually profitability, leading to the end of its life.

Consider, for example, if the interior partitions of a building become undesirable due to a new popular working office paradigm and have to be switched out for the building to be valuable and attractive again in its market. If these partitions are permanently attached to the building's structural system with cast concrete connections, then it may be non-feasible in terms of cost and labour to change the partitions. This means that, in a high-vacancy market, the building could rapidly lose profitability and tenants at the lifespan-scale of its partitions (3-30 years), rather than its structure (30-300 years), and be demolished well before its potential use life is completed. According to O'Connor's (2004) study, the reasons for modern building demolition are primarily related to failure of a building's non-structural layers and an inability to feasibly upgrade them. As explained by Rosen (1996), this concept applies to product-scale objects as well, where designed modularity and ability to separate discrete components enables easier servicing, replacement, and upgrading of specific pieces in a product, rather than wasting the full product.

Life Cycle Analysis (LCA) is a recent digital tool that can precisely quantify the impact of shortened building lives on the amount of embodied energy that is lost. In a 2003 LCA analysis of common building materials, structural steel required the second-highest amount of energy to produce (second only to aluminum), and furthermore the transport costs for steel and concrete were two of the highest embodied energy figures for common material, due to their weight and size (Reddy and Jagadish 2003). A 2010 study by Bribian et al of 60 different buildings across Sweden, Germany, Australia, Canada, and Japan concluded that steel, ceramic, and cement had the three highest primary energy requirements to produce, and that cement and steel produced the two highest amounts of CO_2 emissions in their production (Figure 4). These figures for primarily structural building layer materials compare to relatively low numbers for material that is associated with other building materials or layers layers, such as wood, aluminum, PVC, and others (Bribian et al 2010).

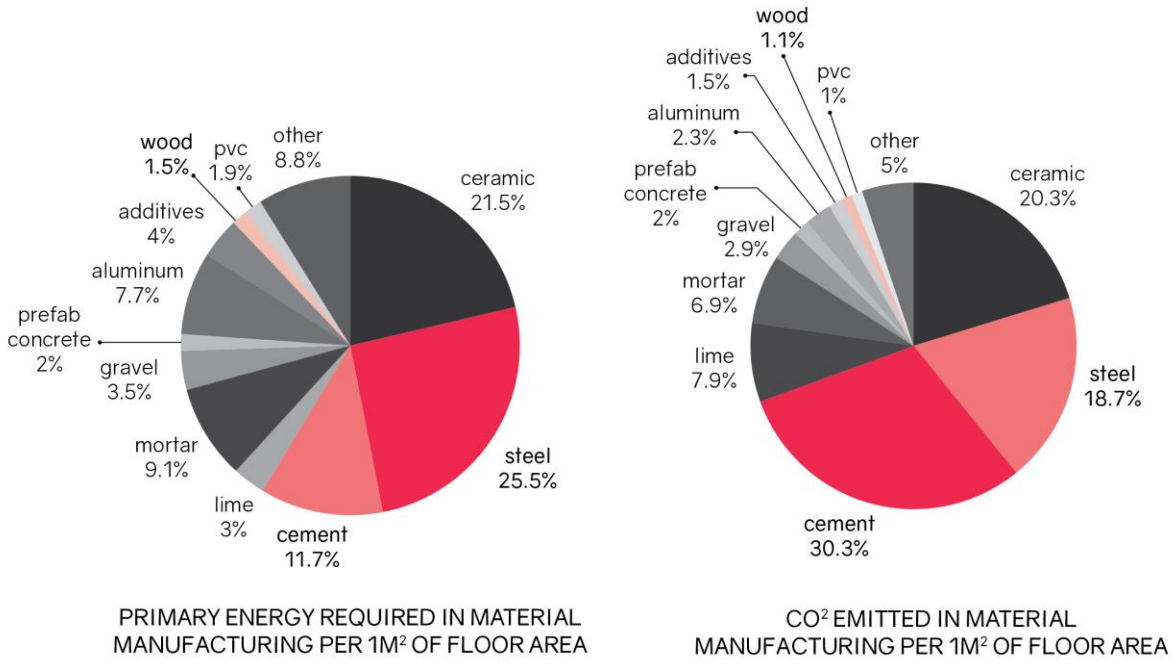


Figure 4: Primary energy requirements for producing common building materials (reinterpretation of a diagram by Bribian et al, 2010)

Pushkar (2015) expands on this research by directly comparing the embodied material energy contributed by each of Brand's (1995) defined building layers across a survey of typical buildings over an assumed lifespan of 50 years. According to this study, the skin and structure layers contribute by far the highest amount of embodied energy and pollution over a building's life, each comprising between 30-40% of a building's total LCA material footprint, compared to under 5% for the services, space plan, stuff, and site layers (Pushkar, 2015). Pushkar's study finds the skin as the highest energetic contributor, however this is due to Pushkar assigning 70% of a building's operational energy consumption to the skin layer (Pushkar, 2015, p. 204) (Figure 5). When the layers are considered from a purely material embodied energy standpoint, structure becomes a slightly higher contributor over skin, according to Menna et al (2013). These studies therefore demonstrate the criticality of ensuring buildings fulfil the full physical potential of their longest-lived material layers, as these layers comprise the highest energetic footprints. However, they also demonstrate the risks of assuming a linear correlation between physical properties and longevity or value.

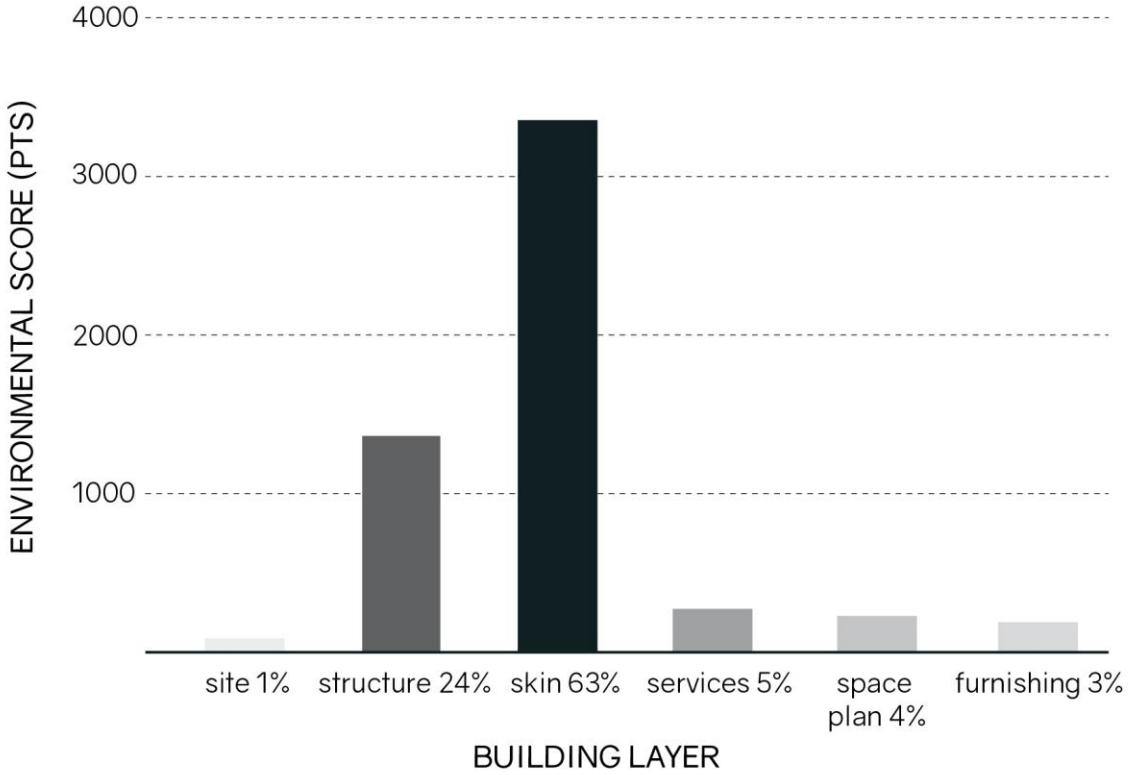


Figure 5: The amount of energy expenditure produced by each typical building layer over its lifetime in a building. The skin layer appears as an outlier because it has been assigned both operational and embodied energy, while everything else except services only contributes embodied energy (reinterpretation of a diagram from Pushkar, 2015)

2.2 Biological vs Cultural Material Durability

The failure of modern buildings to meet traditional metrics of physical durability elicits a central challenge to notions of essentialist materiality, which claim that the value (and therefore the durability) of material is based linearly on its inherent physical properties. This chapter argues that essentialist linear materiality remains an overlying assumption of architectural practice in many ways, evidenced by its tendency to conceptualize and design buildings as permanent entities that function on linear assumptions with limited consideration of broader spatial and temporal contexts. Typical manifestations of essentialist materiality have been observed previously in the assumption that physical strength will make a building or material last longer. However, modern urban contexts have also revealed other essentialist assumptions in practice that relate to the modern economics of buildings. For instance, the linear correlation of built space to economic value may be a form of

essentialist materiality, as many buildings eventually represent negative value (when service/utility costs, tax costs, demolition costs, etc outweigh income) to their owners. Furthermore, the financing period, and therefore primary design scope, for a building typically only lasts between 5 and 20 years (Folger, 2019), thereby neglecting significant factors around building maintenance and end-of-life beyond this period. This chapter therefore begins with the concept of biological, or essentialist, materiality in order to understand how it has produced false models of material value and use life. Biological approaches to material value perception are defined as the essential and intrinsic qualities of material effect that can be observed and felt by humans (Sadalla and Sheets, 1993). These may be traditionally understood as the strength, weight, transparency, colour, or flexibility of a material (Sadalla and Sheets, 1993). Furthermore, with digital tools increasing human cognitive capacity, many classically perceivable material properties such as insulating value or combustibility can now be directly quantified and therefore intensify linear productions of biological value. For instance, Kashef (2010) and Dayaratne (2010) observe the prevalence of thermally-massive material selection (such as stone, mudbrick, and mud plaster) in traditional vernacular architecture of extreme climates such as Egypt and Sri Lanka, respectively. In Sri Lanka specifically, Dayaratne (2010) observed more prevalent use of monomaterial stone construction for open-air public spaces, whereas granaries that had more specific thermal and enclosure requirements tended to utilize composite assemblies of timber frame filled with adobe balls and sealed with lime sand plaster. While the utilitarian properties of each material are clearly understood in these historical examples, applying modern tools to exactly quantify these properties enhances our ability to linearly correlate them to material value.

Vitruvius' notion of "Firmitas" from his *Ten Books on Architecture* represents one of the original concepts of essentialist materiality. Firmitas is one of three key pillars of Vitruvian architecture, referring to the ability of a building to function in a physical sense, essentially whether a building can support itself through regular use, ageing, disaster, and decay (Vitruvius Pollio, 1914). Firmitas is associated with essentialist materiality due to its attempt to convey material durability in an absolute 1:1 linear relationship, where the physical strength of a material such as stone can conceivably enable a structure to survive "forever" (Vitruvius Pollio, 1914, p.22). While the Vitruvian triad does identify other factors in total building design such as Venustas (aesthetic) and Utilitas (functionality), these are considered in a largely siloed manner and fail to account for contingencies and nonlinear relationships between one another. For instance, Vitruvian architecture does not traditionally have a

device by which to explain how the Venustas quality of a building's interior could have an equal or stronger influence over its physical life than its actual structural strength.

A key concept that we may use to understand the essentialist production of material value and its limitations is DeLanda's notion of New Materiality (2015), which critiques the Newtonian and Aristotelean models of absolute materiality. The Newtonian model of material is evident as a linear biological model, in which the identity of any existing object is fully subject to the physical laws of matter that govern it (DeLanda 2015). These laws are upheld as transcendent properties, or in other words objective realities that are not subject to interpretation or nonlinearity. Aristotelean materiality also establishes an essentialist model of materiality, however, describes these absolute properties of a material through its "physical essences" provided to it through its inherent form in reality (Sachs, 2018). The inherent form that defines any material (an organization of elements, such as atoms, that produce resulting physical characteristics) provides it with its set of possible behaviours. A material may adopt one of more of these possibilities over its life, but never deviate from its essential form.

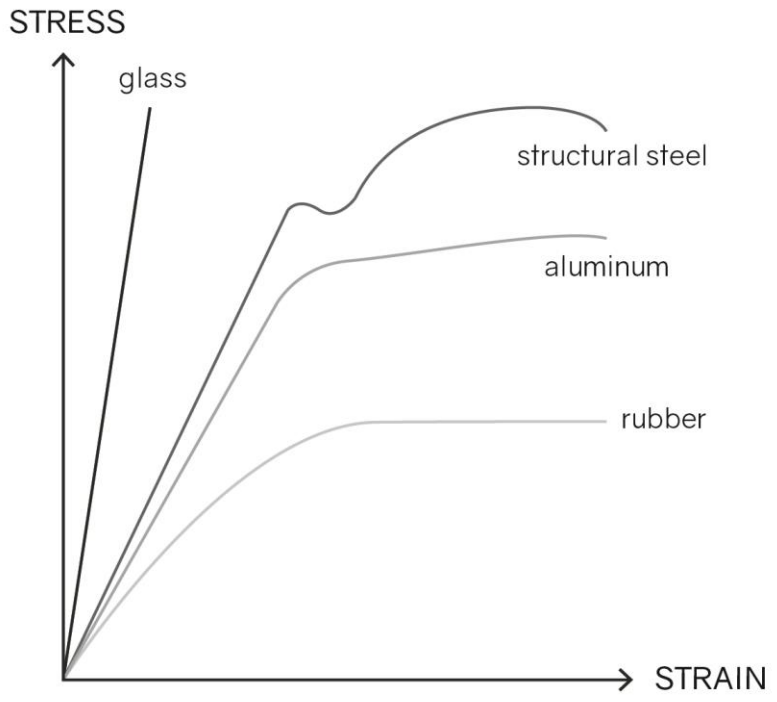


Figure 6: A series of stress (force exerted on the material) versus strain (the response of the material to the force exerted on it) relationships between common materials demonstrates that physical strength is nonlinear. Materials such as steel become flexible at a certain threshold before failing, where glass is brittle and will barely register a response to stress before failing.

DeLanda (2015) uses the concepts of causality and singularity in his New Materiality to explain these essentialist material concepts and suggest their errors. Historically, according to DeLanda (2015), causality in relation to physical material is understood in a linear manner: the same cause yields the same effect always and forever. A given example of this is a structural graph that maps the deformation of material as force is applied to it (figure 6). Though the expectation is that the amount of deformation will linearly correlate to the amount of force that is applied (in essence, the graph will show a straight line), this is generally untrue for a number of reasons. Firstly, some materials only exhibit deformation up to or beyond certain thresholds (yielding J-curve graphs), while others only deform within or outside of a range of force application (yielding S-curve graphs). Secondly, the portion of the material and unique molecular structure of the material upon which the force is applied, the device with which the force is applied, the time interval in which the force is applied, and more factors all affect the material's behaviour and the exact deformation. Causality is therefore nonlinear in its nature, as replicating the exact same conditions of a particular cause to replicate the same effect is essentially impossible.

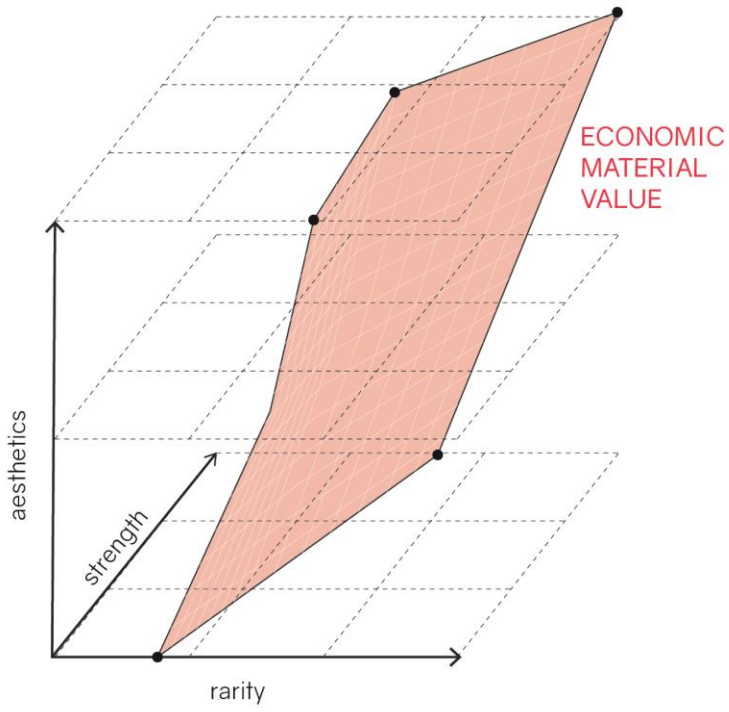


Figure 7: The economic value of physical material can also be expressed as a possibility space. Aesthetic value, strength, and rarity are only a number of possible factors that can affect material value within a certain context of its use.

The "singularity" is the resulting concept that describes how each material has its own specific possibility space for the range of effects and properties it can express under various combinations of conditions (DeLanda, 2015). The singularity is the location in a system where a change in quantity becomes a change in quality. For instance, frozen water, liquid water and boiling water represent three singularities, or unique possible states, within the possibility space of water. Similarly, the relationship between physical properties and value of material is clearly not a linear graph with defined point thresholds, but a multidimensional possibility space that changes throughout the material's life.

Returning to earlier examples of structural material, consider that the economic value of a steel beam in an existing building may be a singularity composed of a highly specific and dynamic set of factors (figure 7). Within the possibility space that determines the beam's value, its structural strength and physical condition is only one axis on which the element gains or loses value and continued use. If the building is at the end of its life, the method by which the beam is attached to adjacent elements may be a significant determinant in its value, since this will determine the amount of labour and cost to recover and reuse the beam itself versus discarding it as part of an assembly. The element's size relative to the standards and design trends of similar building materials at any given time also determine its value, as this will affect its potential reusability for other applications. However, even these mostly quantifiable factors do not directly correlate to a material's value, which is explained through Sadalla and Sheets' (1993, p. 167) second notion of "cultural value."

The more dynamic factors of material value production are referred to by Sadalla and Sheets' notion of "cultural value" (1993, p.167). Unlike biological productions of material value, cultural productions are more socialized and contextually dynamic, as meaning can be produced through aspects such as geographic origins of material (where imported material is often associated with higher social status and value), rarity of material within the area it is used, association with certain social groups and identities in the area it is used, or other contingencies. In Sadalla and Sheets' study (1993), it was concluded that exterior construction materials on houses were able to function as culturally specific metaphors through a process of associative thinking, where the cultural meaning of those materials perceptually defined the interpersonal style, creative expression, and social class of the homeowners (figure 8). For example, survey respondents at the Arizona State University linked red brick facades to homeowners they perceived as being of higher social status and warmer

interpersonal styles, as opposed to concrete block that was linked to lower social status and colder interpersonal styles.

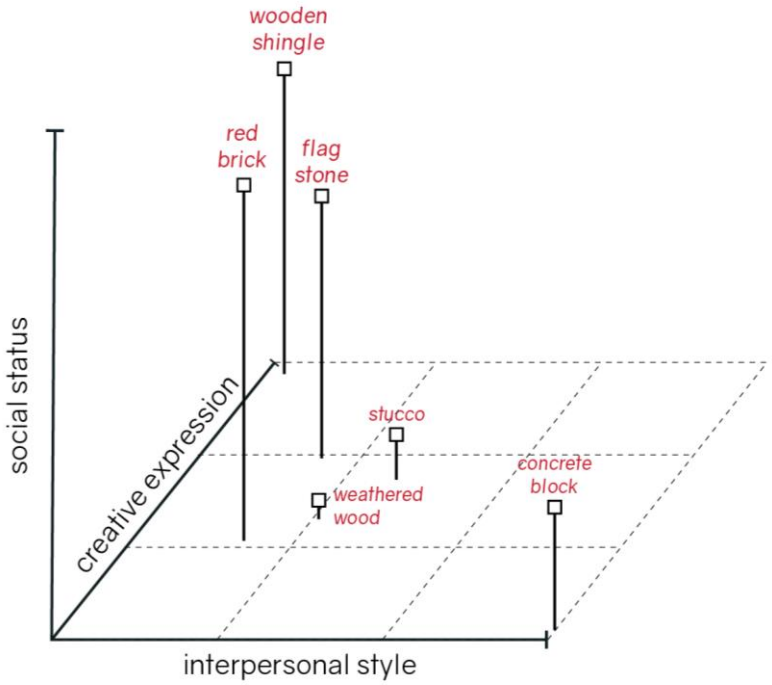


Figure 8: Personality Perceptions about Homeowners Plotted in Three-Dimensional Space (reinterpretation of a diagram by Sadalla and Sheets, 1993)

This theory around cultural value in building materials has many parallels to Levit's 2008 exploration of affect in contemporary building ornament, where affect is described as a relationship between the viewer and building that produces "the physical dimension of the artistic experience." As opposed to Kubo and Moussavi's (2008) claim that affective ornament attempts to free the viewer from social constructs of the symbol, Levit argues that all forms operate symbolically, and affect is therefore a socially-constructed symbolic practice, where decisions such as composition, colour, scale, or other techniques are judged and evaluated through social and historic models of understanding (2008, p. 73). To this end, cultural models of value can and often do directly contradict biological models. Levit provides the example of the proliferation of "greening techniques" in contemporary design, where the at-times non-substantive physical performance of building elements (such as the green roof) is overshadowed by these techniques' identities as cultural symbols for sustainability and the reconciliation of the urban environment with nature (Levit, 2008, p.81).

As noted by Touw (2006), there are several examples of feedback typologies between biological and cultural models that can be observed in modern architecture. One of the most common of these is the cultural notion of "newness value" introduced by Riegl (Lamprakos, 1982, p. 420). Newness-value is largely based on the intense modern pursuit of use-value in buildings, which prioritizes maximum perceived safety and functionality of built space in order to retain its users and therefore economic viability. Ageing and physical degradation of material is a decidedly biological and physical value metric; however, newness-value significantly affects how we perceive the effects of visible material ageing on the material's safety and functionality. According to Riegl (Lamprakos, 1982, p. 420), the overriding paradigm of modern architecture is that only buildings that have significant historical significance and are no longer currently useful gain value from visible ageing of their material. For the rest of architecture, the biological tendency of a material or building to display wear from age therefore increases our cultural tendency to perceive it as unusable or less valuable, regardless of any tangible effect of ageing on its physical condition.

One method to re-conceptualize the difference between biological and cultural material value is through DeLanda's (2015, p. 18) distinction between properties and capacities of material. Properties of material, similarly to biological value models, describe the perceptible and actual physical properties of material, such as its hardness, weight, size, shape, and more (DeLanda, 2015, p.18). In contrast, material also has capacities afforded to it, partially as a result of its specific properties, and partially through how those properties interact with the world and with our perception (DeLanda, 2015, p. 18). These capacities are referred to as being "virtual" (Deleuze, p. 208), meaning that they are indeed real (potential) material traits, however only become actual material traits when they are exercised, perhaps only for a single moment. In DeLanda's (2015, p. 18) example, a knife has the actual physical property of being sharp, but only the virtual capacity to cut things, based on what things it tries to cut and how it is being used to cut them. Therefore, cultural material value might be conceptualized as a virtual capacity of materials and objects, being that their value is only a contingent aspect based on their physical properties, as well as our perception of these properties and their relationship to the systems in which those things operate. The extension of this framework for material value is Meillassoux' (2008) concept of contingency and hyper-chaos. This concept describes the reality that no natural law or physical matter is truly absolute, but rather simply upheld by a specific range of conditions that can change at any time (Meillassoux 2008). Unlike Aristotelean linear materiality, where physical matter is inherently limited

to a possibility space pre-defined by the properties of its being (Sachs 2018), nonlinear materiality describes that the actual and potential states of material are fully contingent on a variety of conditions, and highly specific to each material and its place in space and time. Furthermore, not only material properties, but the laws that govern them, are also contingent. Therefore, according to Meillassoux, the world is in a form of "hyper-chaos," where both physical properties that are governed by assumed natural laws, and the laws themselves, are always contingent.
Through Meillassoux' concept of contingency, we might ultimately conclude that the relationship between biological and cultural value pushes modern architectural design into a form of hyper-chaos. The most assumed physical and economic laws in modern architectural practice, such as that built structures hold value and strong materials last longer, are revealed by modern building lives as being fully contingent on highly dynamic cultural factors. By this interpretation, there is no such thing as absolute physical value (as buildings and material can come to represent negative-value for their owners), or absolute physical strength, only their contingency on cultural factors. That is to say, the subjectively-mediated perception of buildings and materials by users, owners, legislators, etc gains more physical presence and value than the actual physical properties of those buildings and materials.

2.3 Contingencies to Industrialized Construction Adoption in Architecture

To explore the implications of dynamic value models at the building scale, one of the most illustrative movements is the differential adoption of modular industrial construction throughout the world in the post-functionalist mid to late-20th century. The inherent concept behind the industrialized construction paradigm is that major material assemblies and even large building components can be unitized within standard dimensions and tectonic logics, and fabricated off-site in order to increase efficiency and ease of construction, as well as increase the reuse potential of these materials in the future (in an attempt to implement some key tenets of circular design) (Lawson et al 2014). In most cases, modularity (the process of pre-constructing various chunks of building assemblies before transporting them to site) emerged as a response to technical building and urban requirements, with the notion of modularity in modern western construction emerging as a key technique of off-site manufacturing (OSM) methodologies to further reduce environmental impact of construction, increase material efficiency, and offer faster production and assembly (Lawson et al 2014). It is estimated by Boafo et al (2016) that a modular home could produce up to

2.5 times less construction waste than a conventionally-constructed home, while producing 40% less GHG emissions and consuming at least 5% less total life cycle energy due to tighter tolerances. However, despite the numerous observed benefits and existing precedence of industrialized construction, its adoption around the world has not been consistent, arguably due more to cultural reasons than performative ones.

Prior to its contemporary applications in material circularity and OSM, modularity as we know it emerged as result of the 19th-century "Scientific Management" concept (Staib, 2008). This approach involved deconstructing, analyzing, and reconstructing work processes in order to improve their efficiency, and was the base concept behind Henry Ford's assembly line manufacturing model (Staib, 2008). Throughout the 20th century, modularity grew as an architectural response to a series of historical issues in Europe and America, where the largest driver for prefabrication and modularity was the ongoing housing crises throughout the late-19th and 20th centuries. Mass urban migration sparked by the industrial revolution in the late-19th century, as well as World War 1 and 2, resulted in significant housing shortages that were used to invoke the drive for more economical, high-speed, and minimalist industrial production, as opposed to conventional design and construction, in the building industry.

These challenges led to the emergence of "functionalism" as an overarching descriptor of western architecture in the early and mid-20th century, through styles such as modernism and the international style. According to van der Rohe, the adoption of functionalism was an attempt to critique the notion of "style," which he and contemporaries such as Taut believed to symbolize superfluous formalism and predeterminism in architecture, rather than essence and efficiency (Barnstone, 2018). According to Behrendt, "style strove to express the qualities and phenomena of contemporary life in the simplest, most logical and direct manner" (Barnstone, 2018).

The adoption of industrialized architecture was therefore part-and-parcel of this epoch. In 1920s postwar Berlin, housing projects were restricted to only four dwelling types to improve efficiency, while the Great Crash of 1929 in America also inspired Richard Buckminster Fuller's lightweight minimalist "living machine" housing prototypes that were inspired by the engineering efficiency of ships and planes, and could be assembled and disassembled by a single man in under one week (Staib, 2008).

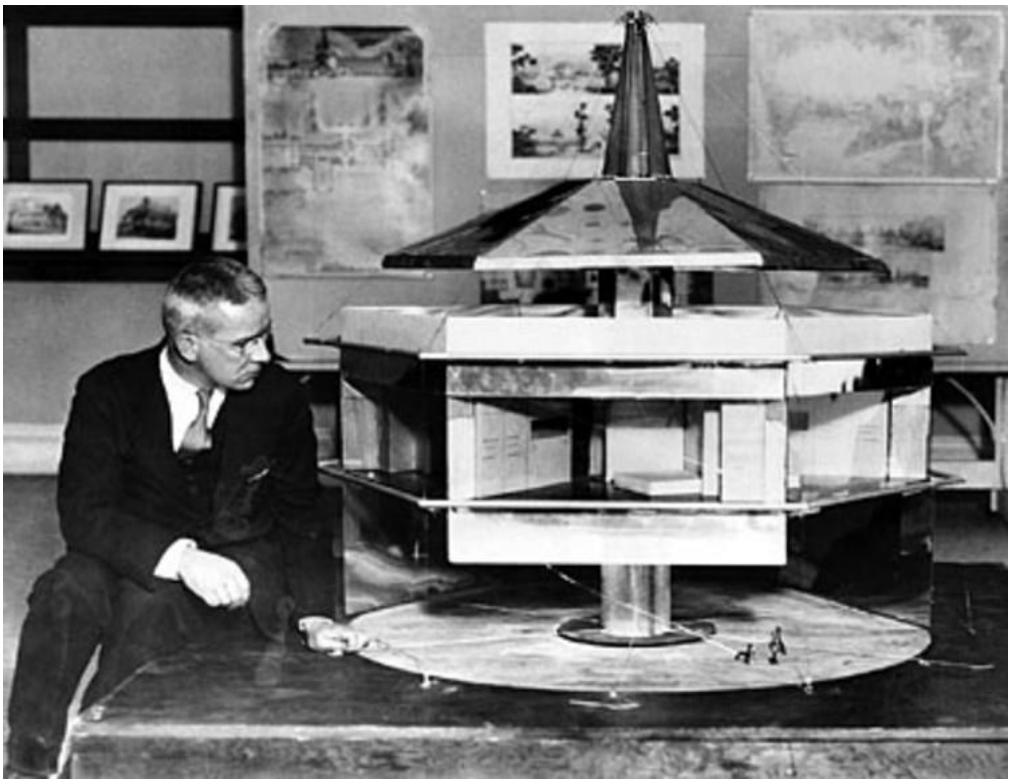


Figure 9: Buckminster Fuller and his Dymaxion House Prototype that would serve as an early exploration of industrialized home construction (Photograph from Bettman Archive, 1930)

Through this period of industrialized housing development however, critical issues were observed in quality and performance of these buildings, where the more complex and larger component modules were more frequently associated with higher rates of building defects (Staib, 2008). Furthermore, the decline of functionalism in the late-20th century gave way to post-modernist architecture in the west, which signaled a cultural shift away from the necessary frugality of wartime and recession-era early-20th century approaches (Urban, 2012). As described by Jencks in 1977, postmodernism represented the resurgence of local traditions, ornament, and symbolism, and accompanied the renewed western interest in private ownership and individual expression. This cultural shift meant that modular construction techniques after the postwar functionalist modern period faced significant social and cultural barriers to their continued acceptance into the later century. In the 1960s market of industrialized modular high-rise development, McCutcheon noted that the significant lack of choice in design, layout, and materials, significantly drove down their demand and social acceptance as housing options (McCutcheon, 1975).

In the late-20th and early-21st century, the prefabricated building sector was seemingly unable to pivot away from its lingering functionalist identity, and therefore the western cultural legacy of modular construction has largely relegated its use to low-cost, temporary habitation typologies that required buildings to be easily and cheaply built and/or moved, such as military and work-camp accommodation, school additions, bathrooms, and more (Lawson et al, 2014). It is through this legacy of modular construction in western contexts that any attempts to increase its market

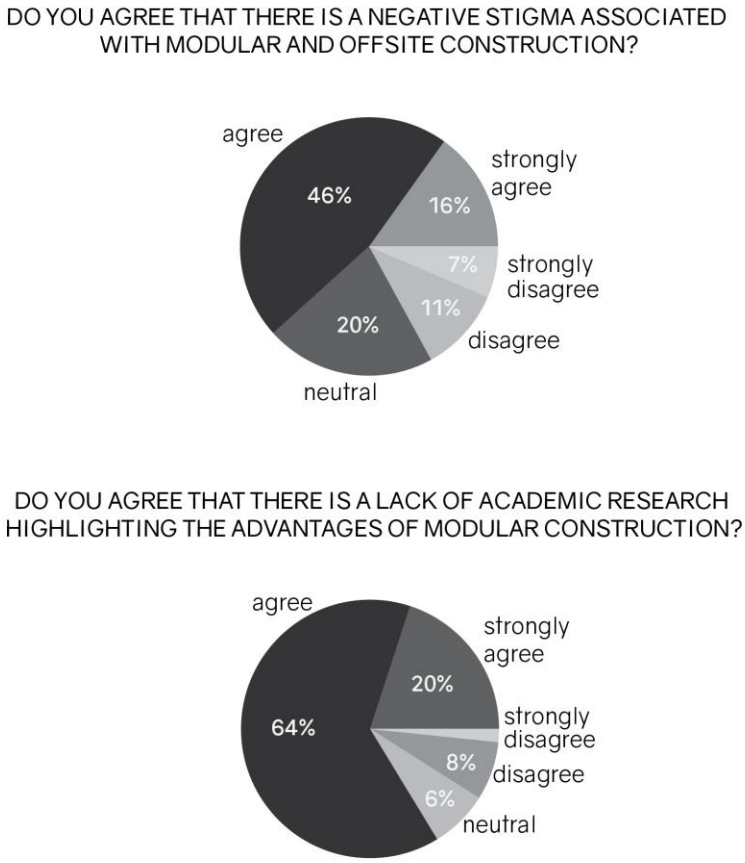


Figure 10: Surveys determining the market perception of modular construction (reinterpretation of a diagram by Salama et al, 2018)

share still observe negative market perception as a significant barrier, despite evidence of its capability to match and often exceed performance of conventionally fabricated buildings (figure 11) (Boafo et al, 2016). Industry in the UK estimated the market share of modular construction for all projects to be only 2.5% in 2018, where over 60% of respondents in an industry survey that year concluded that there was a negative stigma associated with modular construction, and over 80%

believed there was a lack of academic research into the benefits of modular construction, despite its relatively prominent success elsewhere in the world since the late-20th century (Salama et al, 2018). The experience of modular construction in modern western architectural contexts has been drastically different than in Asian contexts, particularly in Japan. This is perhaps most evident in the construction market for housing typologies, which have perhaps the highest stakes in cultural and social acceptance. In 2004, only approximately 1% of homes in the UK were constructed using modular techniques, compared to 14% of homes in Japan (Johnson, 2007). Where western modular home construction in the 1960s and 70s largely failed due to the aforementioned lack of consumer choice and social acceptance, Japan's industrial housing sector began to thrive in the 1970s once housing producers no longer had to focus solely on production quantity, and could instead make heavy investments into design customizability and material quality (Gann, 1996, p. 443). Modern Japanese culture in this era already held a strong trust of industrial production processes after their successful implementation in Japanese car and technological industries, and the increased post-functionalist investments in quality made it even more difficult for consumers of the time to differentiate between traditionally crafted homes and prefabricated homes (Gann, 1996). By the late 90s, when the market share of prefabricated housing had dropped in western contexts, some prefabricated housing suppliers in Japan were offering over 2 million different customer options for housing part selection, where the final construction of many houses still consisted of only 12-15 prefabricated units (Gann, 1996, p. 446).

Figure 11: The Nakagin Capsule Tower by Kisho Kurokawa explored the use of repeatable formal systems to negotiate between infrastructural efficiency and individual expression (photograph by author, 2017)

The cultural perception of modularity in Japan may also be largely attributed to its coincidence with the rise of Structuralism in 1960s architecture, and its synonymity with Japanese notions of collectivism. In postmodern Japan, modular architectural approaches and concepts played a key part in the emergence of the Metabolist movement, which signaled the end of functionalism in the Japanese postwar era in favor of a new "aesthetic consciousness" (Schalk, 2014, p. 282). Similar to the aforementioned Japanese housing industry approaches, Metabolist architecture sought to balance the efficiency and resilience of repeatable urban infrastructures with the freedom of the individual through the same systems-based design approaches first adopted by the Japanese (and American before it) automotive industries (Schalk, 2014). This ethos of mitigating between individualized distinct living spaces and maximized efficiency was a strong driving factor in the post-rational

structuralist era in both Japan and the west. Furthermore, the cell-based formalisms explored through the Metabolist movement in projects such as the Nakagin Capsule Tower (figure 11) strongly paralleled the structuralist aesthetic of other 1960s modular experiments in western architecture, such as Safdie's Habitat 67 (figure 12) or Nelson's Experimental House Model. However, as noted by Urban (2012), it was likely the inherent difference between Japanese collectivist culture and western individualist culture, alongside the Japanese choice to better mobilize techniques of craft to create acceptance of industrialized architectural models.

Figure 12: Moshe Safdie's Habitat 67 (photograph by James Brittain, 2017)

2.4 Contingencies to Synthetic Material Design and Reuse

Examining the lives of modern synthetic materials such as plastics also serves as a case study to demonstrate that essentialist biological value models have little power by themselves to ensure the sustained value required for contemporary material durability and use. Plastic is one of the most technically advanced and flexible materials ever produced by humans, which has led to exponential growth in its production (figure 13) (Geyer et al, 2017) and use for a variety of applications (Van Uffelen, 2008), as well as over a threefold increase in its consumer price index between 1976 and

2015 (US Bureau of Labour and Statistics, 2015). The plight of plastic as a modern material strongly echoes the central problem of circular design, where increasing amounts of energy and labour are involved in creating materials and buildings with increasingly longer technical potential lifespans, however are still failing to remediate the cultural factors that lead to premature obsolescence. Greg Lynn echoes this sentiment in his 2013 discussion on the use of plastic in the contemporary context: "Plastics are so efficient that we throw them away … if there is a way to encourage permanent, and non disposable, use of plastics, then they will become a long-term sustainable solution due to their ease in forming, efficiency, strength-to-weight ratio, and recyclability" (Lynn, 2013, p. 108)

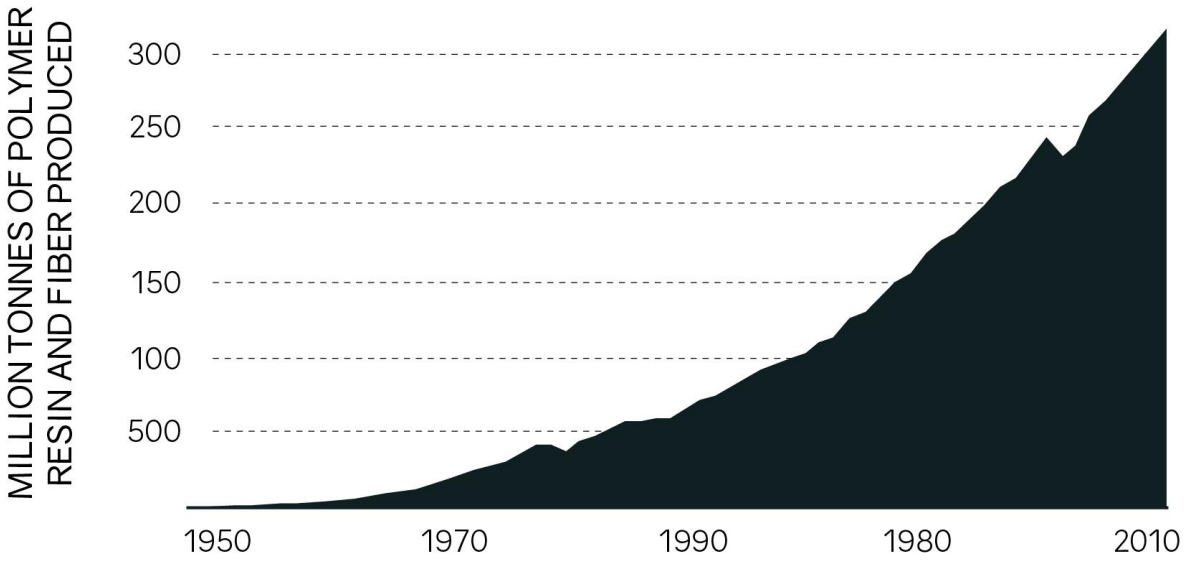


Figure 13: The rapid increase in plastic production since its popularization as a consumer material in the 1950s (reinterpretation of a diagram by Geyer et al, 2017)

Among building materials, plastic's embodied energy-by-volume is equal to that of steel (second only to concrete), and significantly higher than that of glass, aluminum, copper, timber, and many other common building materials (Milne, 2018). Furthermore, many plastic products such as PVC have the mechanical potential to live up to 100 years (Kottas, 2012, p. 12). Yet despite this potential, the mechanical recovery rate of plastic in the building industry generally falls below 30% (Plastics Europe, 2018) whereas the comparative mechanical recovery rate of steel is above 95% for the building industry (Bowyer, 2015, p. 3). As a result, only one-third of all plastics produced worldwide since 1950 are still in production (Geyer et al, 2017), representing a substantial shortfall from the potential life for much of this material (figure 15).

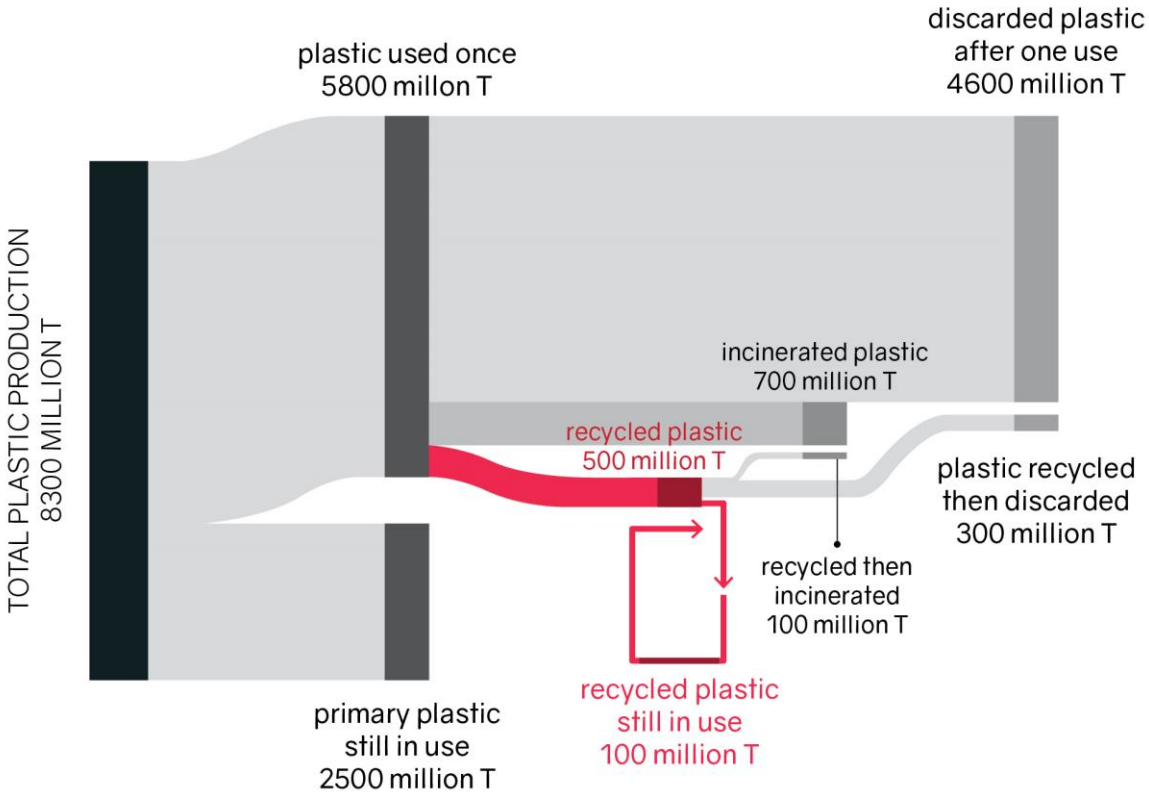


Figure 14: A map showing the life of all plastic ever produced, measured in million tonnes (reinterpretation of a diagram by Geyer et al, 2017)

Perhaps the most illustrative example of plastic's value contingency comes through its transition into a reused second-life material. Virgin plastic has wide technical applications in buildings, such as vapour barriers and piping and is associated with high monetary value in these roles when compared to other materials (Van Uffelen, 2008). However, strict technical requirements for these applications, as well as inconsistent supply chains, make it challenging to utilize recycled content in specific performative roles (Addis, 2006). Therefore, the realm of recycled material is limited to roles such as cladding and surface treatments, where there is a more even stake in both aesthetic and technical performance. This stage of its life is where the key reuse problem emerges, as many reused plastic products do not obtain high enough monetary value to justify their recovery and recycling costs. Based on this life cycle model, Bell (2013) hypothesizes that the artificial devaluation and premature waste of plastic is based largely on its aesthetic identity in a cultural and historical context.

Similar to modular construction methods, plastic in architecture saw a lineage beginning in the pre-functionalist era of the mid 19th century. Otero-Pailos (2013, p. 21) notes that plastic emerged around the same time as other imitative lower-cost materials were introduced, such as the substitution of terra-cotta and cast iron for stone. However plastic's original industry acceptance was based on its capability to prevent building decay and preserve indoor air quality. As such, the first major use of plastic in architecture was rubber-based paint used in the late-19th century to counteract the rapid building and air quality decay incurred by the pollution in the early industrial revolution (Otero-Pailos, 2013, p. 23). This application of plastic expanded into other molded ornamental products such as Lincrusta in the early-20th century (figure 15). The first fully synthetic plastic, Bakelite, was introduced in the 1920s and commonly used to mimic painted wood, with the claimed benefit of being more hygienic (Otero-Pailos, 2013). However, the advent of modernism and functionalism in the 20s and 30s signaled the death of these kinds of applications, and a move towards minimalist surface-based aesthetics (Colornina, 2013, p. 30). Hygiene and sealing-based concerns resulted in plastic's subsequent use mainly in piping and other laminate wall and furniture surfaces (Otero-Pailos, 2013, p. 26).

Figure 15: Paul T. Frankl's "Skyscraper Cabinet," using Bakelite plastic laminate (photograph by Frankl, 1927)

In 1956, Alison and Peter Smithson developed the "House of the Future," built to imitate seamless molded plastic surfaces and filled with plastic objects such as custom folding plastic chairs, nylon and latex foam bedding, fiberglass curtains, and Tupperware containers (figure 17) (Colornina, 2013, p. 30). As Alison Smithson suggested, the translation of the house into an industrialized, mass-producible consumer product signaled the post-functionalist cultural desire to reject over-standardization of industrialized production, and instead use these production methods to develop a series of unique molded shapes and forms (Colornina, 2013, p. 36). However, the ultimate irony of this prototype was that none of the house's building materials were actually plastic, but conventionally built assemblies of plywood, plaster, and emulsion paint meant to mimic continuous surfaces (Colornina, 2013, p. 36).

Figure 36: Alison and Peter Smithson's "House of the Future," mimicking surface continuity of moulded plastic

Similar to previously discussed modular techniques, plastics in architecture also saw popularization through the futurist works of Buckminster Fuller, and had a peak moment in design consciousness at the Montreal Expo 67 (Wigley, 2013). Wigley notes that Fuller had been using plastics since his Dymaxion house prototype in the 20s (2013, p. 82) to seal the interior, and. Fuller's plastic use peaked at the Expo 67 with its use as the transparent surfaces of his iconic geodesic dome (figure 17). While plastic played a crucial role in enabling Fuller's visions, Wigley (2013, p. 68) points out that its seeming invisibility across those 40 years of development set the tone for its contemporary proliferation as an imperceptible material with little emotional or cultural attachment. The contemporary house has, in a way, achieved the dream of the plastic house envisioned in the Smithsons' 1956 prototype, where we now unwittingly live amongst acrylic paint, polyurethane floors, PVC piping, laminate trim, vinyl siding, and countless other plastic materials.

According to Wigley (2013, p. 68), the key epistemological differentiation between our understanding of plastic as a designed object when compared to traditionally endearing objects is our inability to imagine plastic functioning independently as the object itself. Eames and Saarinen, prominent practitioners in plastic design for interior objects, expressed hesitance at applying plastic in architectural scales. They stated that the formal softness of plastic created an immense challenge for discerning any legible material quality and affect when plastic could be "anything it [wanted] to be" (Lavin, 2013, p. 18). Considering our lessons from western modular construction, Eames and Saarinen's cautionary note suggests how the formal and material efficiency of plastic has culturally relegated it to applications of architectural technical and economic functionalism, rather than of design and value. Thus, the lingering original connotations of plastic as a technical mediator between interior and exterior have overpowered its brief late-century reign in expressive furniture and surface

experimentation, and resulted in what Wigley describes as a material "we are almost always looking at, through, and from, and yet rarely seeing" (2013 p. 68).

Therefore, Bell (2013) proposes that the inherent devaluation of reused plastic for building materials is closely linked to this lineage of design decisions that established its cultural connotations as a cheap, artificial, and invisible material. These decisions are based on designing plastic in a manner that is purely imitative of other standardized material affects, where Otero-Pailos (2013) states: "Plastic does not know what it is, so it finds itself becoming every other material around it … we have realized a world of plastic versions of previous building components – vinyl-clad wood windows, vinyl wood siding, etc – now employed in ways that sustain former vernaculars (histories rather than futures), simultaneously casting our gaze forward materially and backward formally …(p. 13-21). Through a case study examination of projects by post-functionalist designers such as Greg Lynn, Bell (2013) suggests that addressing the life cycle of plastic should focus on leveraging its ability for unique material affects and flexibility in order to produce a more culturally-valuable and distinct material identity that can function outside of purely technical and utilitarian applications.

Figure 47: Buckminster Fuller's Geodesic Dome, utilizing a steel frame and plastic panels

2.5 Conclusion

As paralleled in DeLanda (2015) and Meillassoux' (2008) concepts of materiality and contingency, the dynamic production of architectural value and durability results in a form of contingency that disproves any linear relationship between physical performance and economic value. The inherent physical properties and strength of materials have been reduced to a negligible role in their actual value and use lives (Touw, 2006), as the physical and economic standing of material has become almost fully contingent on cultural factors of value production. The initial rise and late century shift of these two case studies over the rationalist and post-rationalist eras, respectively, exemplifies two different examples of contingency in architectural production. Despite its high biological performance and applicability, plastic became more disposable and a larger negative value proposition for the world due to cultural perception on its use and reuse. Similarly, despite its high technical potential for sustainability and quality, industrialized production failed through its cultural disassociation with craft and individuality. The industrial revolution and rationalist periods sparked, for the first time, humanity's nearly full control over material (fully synthetic plastics) and organization (industrialized construction and material logistics). However, these new elements also exemplified the true degree of cultural contingency in the physical value of architecture.

Therefore, we end up at the uniquely false permanence of architecture, predicated on the idea of "durability in the form of mass and solidity" (Touw, 2006, p. 26). Based findings of all the contingent influences involved in the chaotic value production of material and architecture, this chapter must conclude with Ford's (1990, p. 4) claim that "neither concepts nor forms are permanent, and both are perhaps disposable." This therefore falsifies any notion that architectural permanence can be achieved at the consistent scale of the physical object, whether that is the object of the material component or the object of the building itself. Lynn's assertion that contemporary synthetic materials and their architectures may solve many of the world's problems of waste if used in a permanent manner (2013, p. 108), therefore presents permanence as a significant conditional statement.

As explored by Ford (1990), futurist and high-tech architecture of the late-20th century attempted to challenge the traditional notion of permanence at the scale of the architectural object by attempting to conceptually re-frame buildings as industrial products, and thus acknowledge their impermanence and transience. This involved adopting industrial product design techniques such as utilizing specialized discrete building components over monolithic assemblies, planning for the failure of

components and systems, and designing for regular maintenance of these components and systems. This newer paradigm challenged the conventional object-based scale of architectural permanence by designing for the event-scale instead, by considering possible changes in contingent factors that would cause buildings to lose value (material degradation and failure, tenant turnover, and market shifts for example). By better enabling upgrading, maintenance, and replacement of component building systems, these late-century paradigms suggested that building permanence was not a question of consistent physical form in the built object, but on flexibility of the building to various conditional changes over its lifetime.

Touw (2006, p. 4) defines this new event-focused model as "dynamic permanence," wherein material preservation, rather than formal preservation, is prioritized. Similar to the tenets of futurism, this means that a building's most valuable material systems may be enabled to last longer by allowing the building's shorter-life systems to change more easily. However, Touw's (2006, p. 4) more provocative suggestion through dynamic permanence is that the measured durability of a building is not even in the building itself, but in its smallest physical component parts, which each have their own possible use models once they are no longer limited to the static location (in terms of geography and of use) of a single building. Furthermore, as with the building, the permanence of these materials may not be measured by the consistency of their physical form over time, but by the consistency of their smallest energetic and material components. This model acknowledges that materials often have to transform physically in order to preserve their embodied energy and value for as long as possible.

Therefore, the key avenue for future development of contemporary permanence are the exploration of non-object-based scales in the practice of architectural and material design. This includes the consideration of how a building or material's smallest component parts may find distributed value throughout a longer use life by becoming less limited to singular physical forms and locations.

Chapter 3

Contemporary Design Event Scales and the Circular Economy

The modernist architecture movement of the early and mid-20th century was strongly associated with the notion of "logical positivism," a concept that claimed architectural design and materiality could be distilled down to fundamental and reliable objective knowledge (Galison, 1990, p720) in order to address modern issues. Accordingly, the medium this movement was most concerned with was physical materialism, and it therefore placed the utmost importance onto the physical "object" (a building, product, or otherwise designed assemblage of materials) and its spatial performance (DeLanda, 2008). As written by Salgırlı (2018, p. 49), modernism would therefore re-shape social and cultural systems around it through the power of the concept and the physical object. This model firmly established the concept and the object as the primary scales of concern for architectural design, as this object acted in a top-down hierarchy to form the social and cultural contexts beneath it. However, by attempting to establish the material object and its performance as absolute properties, modernism created buildings and products that were exceedingly vulnerable to broader scales of influence and contingency from outside the limited physical scales considered in their design.

Bernard Tschumi's postmodernist projects such as the 1982 Parc de la Villette in Paris signified a significant change in scale thinking for the architectural object. In contrast to modernism, Tschumi's Parc suggested that the architectural object must be produced by considering the changing use possibilities that its broader spatial and temporal contexts present, and that architecture should focus on producing spaces that are activated and shaped by the subsequent events in and around them (Salgırlı, 2018, p. 49). This notion, which Tschumi coined the "Event City," framed a new paradigm of design in which the architectural object ceased to represent the scale of the concept and physical form, and instead began to represent the broader scale of the "event" (Tschumi, 1981). Parc de la Villette, for instance, sought to pursue indeterminacy in the form and function of its physical follies, in order to address the multiplicity of use circumstances and cultural contexts they would likely face over their lives (Tschumi, 1981). As described by Eisenschmidt, these "multiplicities of circumstances" (2012, p.19) in the modern urban condition inherently threatens the existence of architectural objects that are unable to adapt.

Today, design paradigms are re-engaging the notion of the event in design to consider the distributed physical, temporal, and economic scales involved in the material life and durability of contemporary architectural objects, such as their manufacturing, transport, use, reuse, and disposal. In response to growing contemporary crises such as climate change and resource scarcity, the

engagement of the event scale in current design primarily involves addressing the mechanisms by which designed objects lose and regain value throughout their lives. The material problem presented by this new event-scale acknowledges that responding to all possible contingent factors over the potential lifespan of most materials is impossible to do through a single physical form (Touw, 2006, p. 13). Therefore, rather than addressing durability and value on an absolutist physical level where physical form must stay consistent, this new method of design argues that the architectural and material objects should be adaptable at their smallest possible components (a notion referred to as "dynamic permanence") in order to be truly durable (Touw, 2006, p. 4). This means factors such as recyclability, flexibility, and modularity are all becoming key design concerns to reduce waste and optimize material life.

One of the most prominent frameworks in this new scale of design is the "Circular Economy," which was built on Walter Stahel and Genevieve Reday's (1976) "Cradle to Cradle" concept (a term which would later be popularized by McDonough and Braungart in their namesake 2002 work). The Circular Economy attempts to minimize waste generated by consumer products by describing a wide range of possible events that will affect a product's value across its whole life, and new relationships and methods to anticipate those events. These events delineate both physical aspects such as the ability to recover, sort, and process a product into a new one and economic aspects such as the ability of product end-of-life to provide positive and negative financial feedback for designers and producers at the product's beginning-of-life to optimize material life. Similar to Tschumi's Event-City, which argues for the possibility of design feedback and influence from unanticipated downstream uses and occupations of space, the Circular Economy creates design feedback from downstream disposal and reuse of products through new physical and economic relationships.

This chapter therefore questions what the Circular Economy is as a contemporary scale of design-event for material, in order to translate "dynamic permanence" (Touw, 2006, p. 4) into tangible design criteria to address conventionally imperceptible physical, temporal, and economic scales. To this end, this work discusses the historic scalar evolution of design from modernist mid-century architecture to postmodernist late-century architecture, and into current contemporary circular architecture. Building off this historical context, the work identifies a series of 21st-century case studies that attempt to address various material design scales created by the Circular Economy. Through this study, this work aims to identify the Circular Economy as a new event-focused design

concept and suggest how it may turn imperceptible downstream events into tangible object design feedbacks.

3.1 Post-Modernism and the Event-Scale of Design

One of the key failures of modernism resulted from the assumption that architecture could exert an absolutist physical formula to shape built space and its related socio-cultural and economic models, and therefore free design of considering the agency of these models to exert their own influence. The move from modernism to post-modernism therefore represented a wholesale rejection of rationalist approaches that privileged the power of essentialist physical materialism over all else. This new architectural framework therefore "demanded rationality and functionalism" and resulted in what was referred to as an aesthetic "antiaesthetic," that claimed to shun stylistic concerns in favour of objectively-provable design (Galison, 1990, p. 711). As explored in chapter 1, this approach was strongly popularized by postwar issues such as housing shortages, and therefore valued objective materialist development above all else.

In the late-20th century, Tschumi developed "The Manhattan Transcripts" (1976-1981), which established the nature of the "event" in built space. In these works, Tschumi diagrams various series of transgressive uses of architectural space in order to explore inconsistencies between these spaces' architectural form and the activities that occur within them. The diagrams of these uses are subsequently formalized as proposed architectural objects with legible relationships between form and activity. Through these pieces, Tschumi argued that the three key considerations of architectural design (use, form, and social values) often relate but almost never coincide, therefore making it architecture's job to recognize their interconnected relationships and find a reasonable balance. However, the "event" is then framed as a qualitative threshold, similar to Meillassoux' "singularity" (2015), at which these factors and their relationships can be changed and destabilized. For instance, Tschumi's diagram of a murder in a built space represents an event with drastically different social values and use, and therefore radically questions the built form of the space in which it occurs (Figure 18).

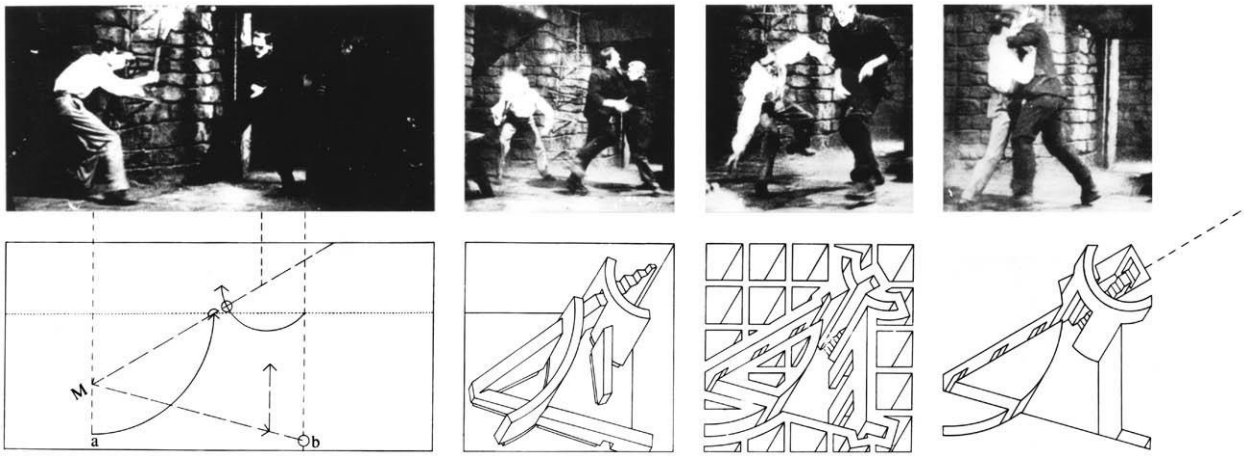


Figure 18: Imagery from Bernard Tschumi's "Manhattan Transcripts" (from Tschumi, 1981)

The emergence of postmodernist concepts around expanded design scales explored in "The Manhattan Transcripts" birthed additional exploration into the notion of scale, exemplified in Bernard Tschumi's "Event-City" works. The concept of the Event-City demonstrated an ambition to redefine the scale of architectural design in regards to time and space, by removing the object from the top of the hierarchy and replacing it with the event. Tschumi's notion of the Event-City asserted that architecture was defined primarily by the "event" that occurred in or around it, rather than the physical "object" that had power to shape everything inside and around it (Tschumi, 1994). This event was characterized by the multiplicity of the city around the architectural object, which was constantly growing, changing, and redefining itself. Through this precedence of the event, architecture was forced to consider two-way relationships between built space and its various contexts over an entire lifespan, and therefore expand the scope of design beyond a singular space, time, and economy.

Bernard Tschumi's 1982 Parc de la Villette project (Figure 19) in Paris presented a physical exploration of these concepts, where various prospective uses and social values were used to generate a series of physically and programmatically indeterminate follies. These follies provided adaptability to a wide variety of possible activities and were mapped along a grid of lines to capture a variety of possible movement through the park (Tschumi, 1982). In a 2012 interview, Tschumi states that the key distinction made by Parc de la Villette was its "distinction between defining space and activating space," producing objects that "activated space and generated energy – almost creating fields of magnetism" (Eisenschmidt, 2012, p. 133). Through this technique of attempting to under-

define form and use, these follies attempt to allow for the contingency of future events that may threaten the conditions of their existence.

Figure 19: Four of the 35 built folies at Bernard Tschumi's "Parc de la Villette" (photographs by Nils Jonsson, 2013)

These ideas were further developed through Tschumi's four "Event-City" volumes, which detailed explorations of different types of events considered in various built and proposed architectural projects between the 1990s and 2010s. Tschumi's four "Event-Cities" works describe the dynamic condition of the modern city as a highly dynamic and indeterminate organization of use, form, and social conditions that evades control. Therefore, projects in the first "Event-City" volume, such as the 1988 Kansai International Airport, examined contemporary urban typologies that demonstrated similarly dynamic event-driven models of multiplicity and change as cities themselves, and detailed Tschumi's ambition for architecture to better reflect and participate in this process (Eisenschmidt, 2012, p. 135). In the first "Event-Cities" (1994) work, Tschumi alluded to broader spatial scales of event in architectural production, since design considerations for programs such as airports and railway stations had to incorporate the potentially worldwide spatial and economic relationships created by globalized transport. Furthermore, Tschumi also acknowledged the inclusion of advanced

temporal and economic scales in these programs, due to their inherent need to expand and grow (Eisenschmidt, 2012). As a "microcosm of the city" (Eisenschmidt, 2012, p. 134), programs such as airports would therefore see a stronger influence from events that were further removed from their defined location in space, time, and economics.

Tschumi's notion of the "event" as a design driver draws strong implications to Deleuze's theme of the "virtual" discussed in DeLanda's (2015) "New Materiality" and introduced in chapter 2 of this thesis. The concept of the virtual is used to draw a distinction between properties and capacities of materials; in other words, the actual characteristics of the material (properties) and how these characteristics can potentially be used, or "actualized," in various relationships (capacities). This concept is pertinent to Tschumi's work in the sense that a physical piece of architecture might be seen to have actual properties, however also a broad series of capacities, depending on how the building's properties interact with the social, economic, cultural, and urban context in which it exists. The event represents this interaction that actualizes or de-actualizes capacities of architecture. Tschumi, therefore, pioneered new broader scale thinking in design by recognizing the agency that the event has to de-actualize a building's usefulness, value, beauty, and more, and subsequently prioritizing capacities in the design of architecture.

3.2 Circular Economy and A New Event Scale for Materiality

The Circular Economy represents a new contemporary scale of "event" for the design of objects. The Circular Economy optimizes material life by anticipating how material will become devalued and discarded at the end of its use life, and subsequently proposing design techniques and business relationships to address how to retain value and energy instead of discarding material (figure 21). This includes identifying and addressing events that can waste material, such as market fluctuations, failures of various physical layers, shifts in aesthetic trends, and more. One key tenet of the Circular Economy is the notion of "dynamic permanence" described by Touw (2006, p. 4), which states that durability of architecture and materials can no longer be dependent on longevity of a single physical form of material or parts. Instead, the scale of durability has shifted to the smallest scale of contingent parts, in order to facilitate maximum adaptability to the various types of destabilizing events across the object's life span (Touw, 2006).

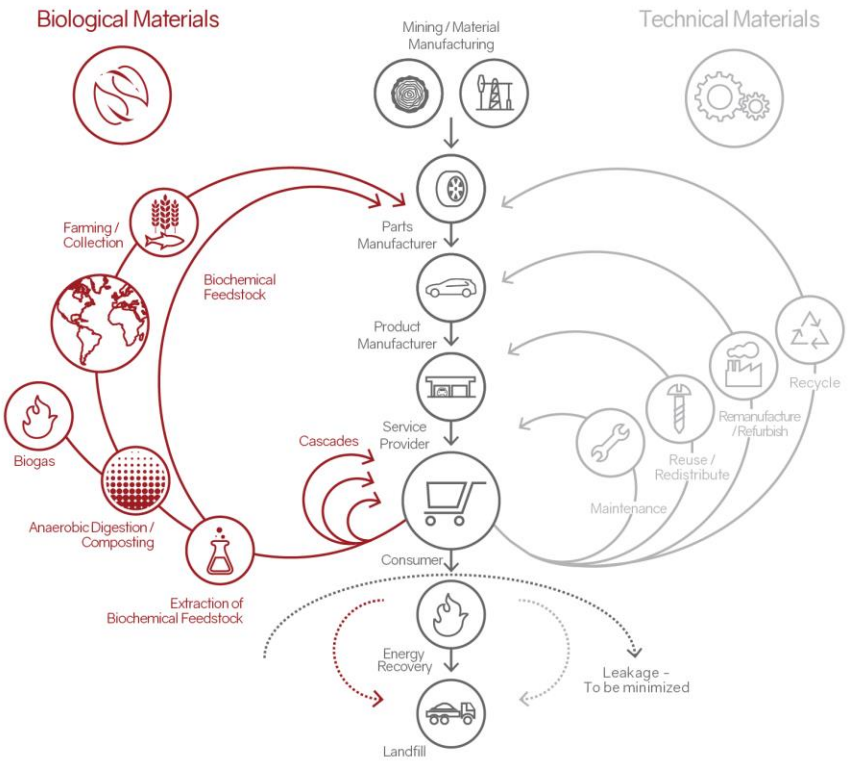


Figure 20: A map of the possible technical and biological reuse cycles at the end of a material's life (reinterpretation of a diagram by the Ellen MacArthur Foundation, "Growth Within," 2015)

The popularization of the Circular Economy concept in the 21st century has produced a wide variety of interpretations into its exact scope and definition. While Desrochers (2002) acknowledges the existence of circular material reuse principles since the beginning of industrialization, one of the key differentiations of the Circular Economy is its ambition to, at the initial design stage, recognize and address siloed material life cycle processes that create significant capital losses in current linear models of material reuse (Korhonen, Honkasalo, and Seppälä, 2018). It is acknowledged that thermodynamic limits ensure there will always be some linearity in material systems (Korhonen, Honkasalo, and Seppälä, 2018, p. 43), therefore the Ellen MacArthur Foundation (2015, "Towards a Circular Economy," p. 5) defines a working Circular Economy as a system built on a "positive development cycle that preserves and enhances natural capital, optimizes resource yields, and minimizes system risks." This new framework involves tackling the systemic moments of value-loss

created by "spatial and temporal system boundaries," and developing systems approaches to the cooperation of producers, consumers and other societal actors in sustainable development work (Korhonen, Nuur, Feldmann, and Birkie, 2018, p. 42).

The key advancement made by the Circular Economy over notions such as the Event-City is a shift in scale from the life of full object assemblages such as buildings (which have discrete phases of production, use, and removal) to the lives of their component parts that hold usable value and energy. This new model acknowledges that the use value of products and buildings will never be permanent, but that waste can be avoided by ensuring that the use value of their component pieces can be maintained and adapted for new applications beyond the lives of single products/buildings (McDonough and Braungart, 2002). Therefore, the Circular Economy defines events at the scale of the material life, rather than the object life. These events, such as transport, assembly, maintenance, disassembly, re-manufacturing, and disposal all present potential pivotal moments with design implications that affect the use life and value of the material.

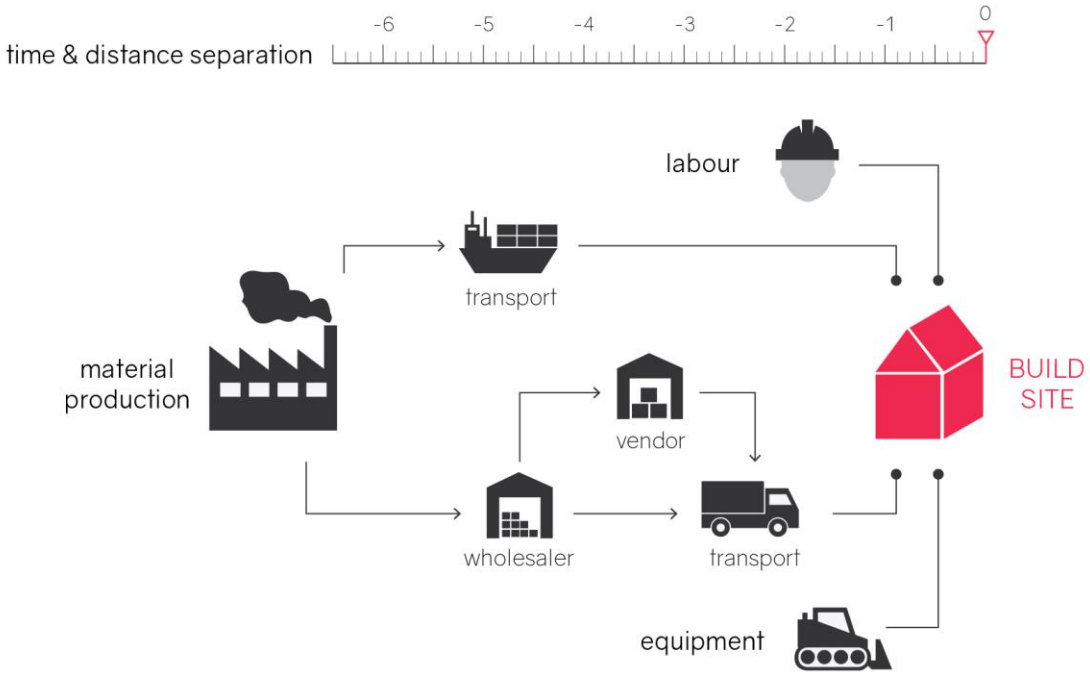


Figure 21: The process of standard construction logistics, in which material, labour, and equipment converge within a specific location and timeframe to produce a building

The scale shift implicated by the Circular Economy is largely due to the additon of "reverse logistics" into the design process, which refers to the reverse flows of material from buildings and consumer products for the purposes of recycling and repurposing (Pacheco et al, 2018, p. 1451). In conventional design processes, logistics describes a relatively uni-directional series of events in time, space, and economics, where the material design choices of a designed building or object are contingent on the demands of bringing material to a distinct site, within a distinct period of construction time, and within a distinct project budget (figure 21). The addition of reverse logistics into the material supply chain is critical because it de-localizes the spatial, temporal, and economic demands of material design (Beamon, 1999). The removal of specific material from a site can be distributed throughout time (because different systems have different intervals of replacement), space (different materials will be removed to different facilities for sorting, recycling, and/or disposal), and economic models (different materials have changing costs and profits over time to recover and recycle into new material). (figure 22). These broader scales suggest that Touw's (2006, p. 4) notion of "dynamic permanence" might be alternatively termed as "distributed permanence," considering that the events that affect material use and reuse are widely distributed through broad scales of space, time, and economies.

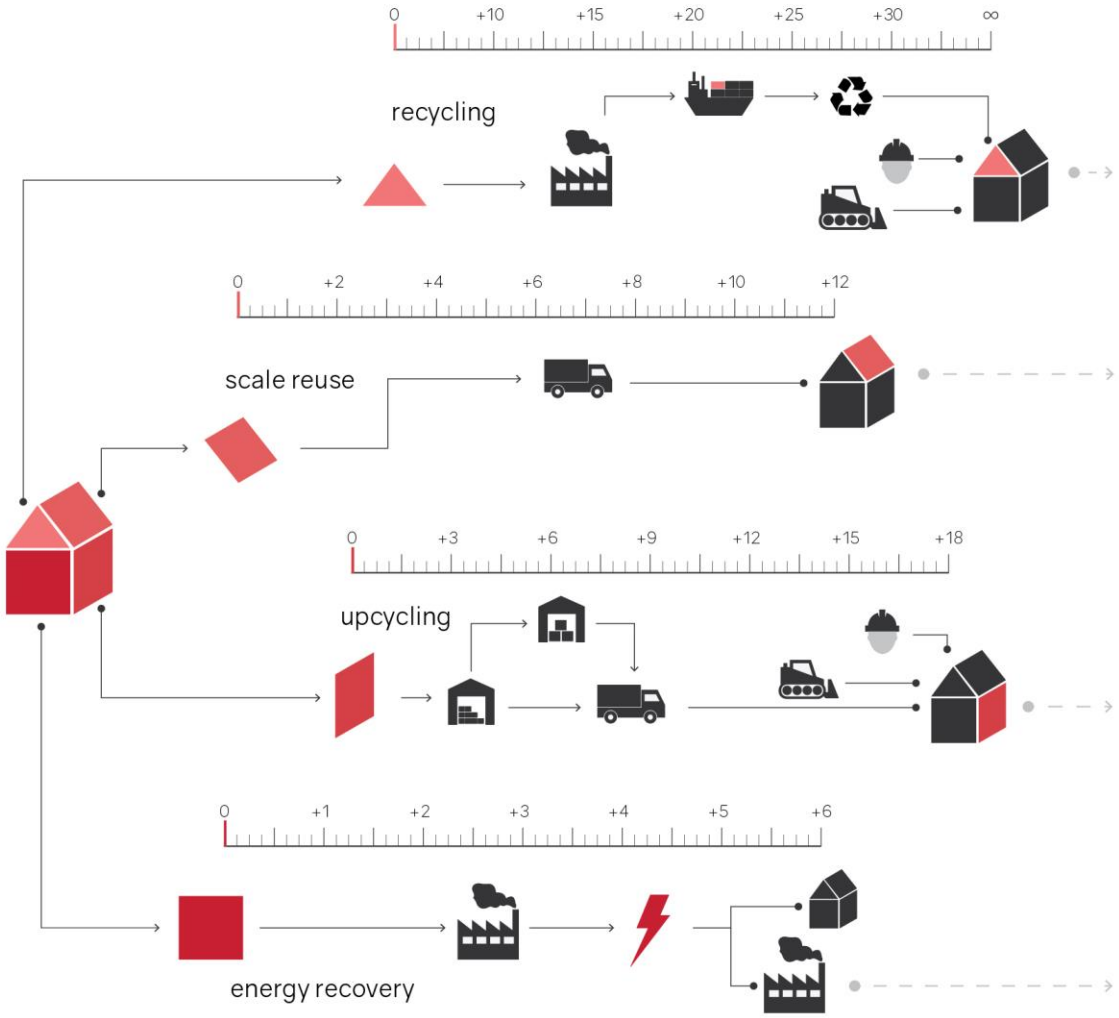


Figure 22: The process of reverse logistics, where management of materials, labour, and equipment is based upon distributed, non-localized demands for the material's use in subsequent applications, rather than the localized demands of the building

3.3 Circular Design Overview:

The broader-scale events of the Circular Economy have produced new design models that function to consider these new scales of space, time, and economics within the initial design process. "Circular Design" is the overarching concept to describe strategies for addressing object design at the level of the material life cycle. In order to shift the focus away from object-based physical permanence and into material-based distributed permanence, Circular Design places significant emphasis on the metric of "embodied energy" (figure 23), which describes the total amount of

energy required to produce a material or object, including for the extraction, processing, manufacturing, and disposal of said material or object (McDonough Braungart Design Chemistry, 2008, p. 10). The focus on embodied energy means that metrics such as efficiency, lifespan, reusability, and cost can be directly informed by the base energetic properties of a material or object, and therefore incentivize scaled material thinking beyond the physical object.

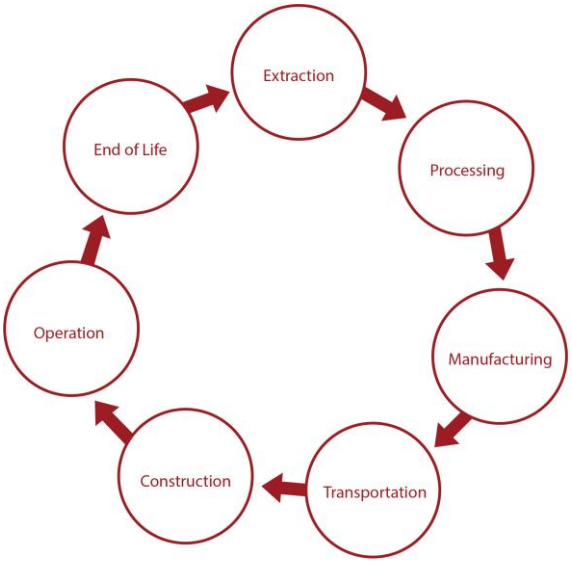


Figure 23: The events of a material life cycle that affect its embodied energy quantity (Guldager-Jensen et al, 2019)

Circular Design comprises a variety of strategies across its field of practitioners, however it may generally be understood through three interdependent categories of technique. Since conventional object-based design methods are challenged by the temporal, physical, and economic separation of the design process and extended reverse material logistics, the three main strategies of Circular Design can be seen to represent methods to bridge these three disconnects. In their literature review on Circular Design approaches, Moreno et al (2016, p. 3) distinguish three categories of "design for resource conservation" (primarily relating to physical factors such as reduced material use and lighter weights), "design for slowing resource loops" (primarily relating to temporal factors such as designing for remanufacturing and timeless aesthetics), and "whole systems design" (primarily relating to economic factors such as designing for value chains). In a more simplified interpretation, Ordonez and Rahe (2013) interpret these challenges in their establishment of three scales for material reuse design: designing for durability (bridging time), designing for end-of-life (bridging physical form), and designing for reused materials (bridging economics).

Guldager-Jensen and Sommer (2016) provide a more comprehensive architectural framework of the time/form/economics equation that proposes Material Passports (bridging time), Design for Disassembly (bridging physical form), and Design for the Circular Economy (bridging economics) as the main strategies. Material Passports bridge the time-scale disconnect by providing methods to easily track relevant material properties over their whole life in order to reduce uncertainty about their condition, composition, and/or performance. Design for Disassembly (DFD) involves bridging initial design with end-of-life material transition by facilitating easy physical separation, recovery, and/or recycling of component materials from their respective objects. This means avoiding composite materials and assemblies that are not mechanically separable, such as sealants, casted connections, and welded connections. Lastly, Design for the Circular Economy bridges long-term economic disconnects in the design process by identifying new business synergies produced by synching value inputs and outputs at various stages of a material life. For example, the cost to remove and dispose of material based on its design can be a significant feedback to the design process if building demolition is factored into the project budget.

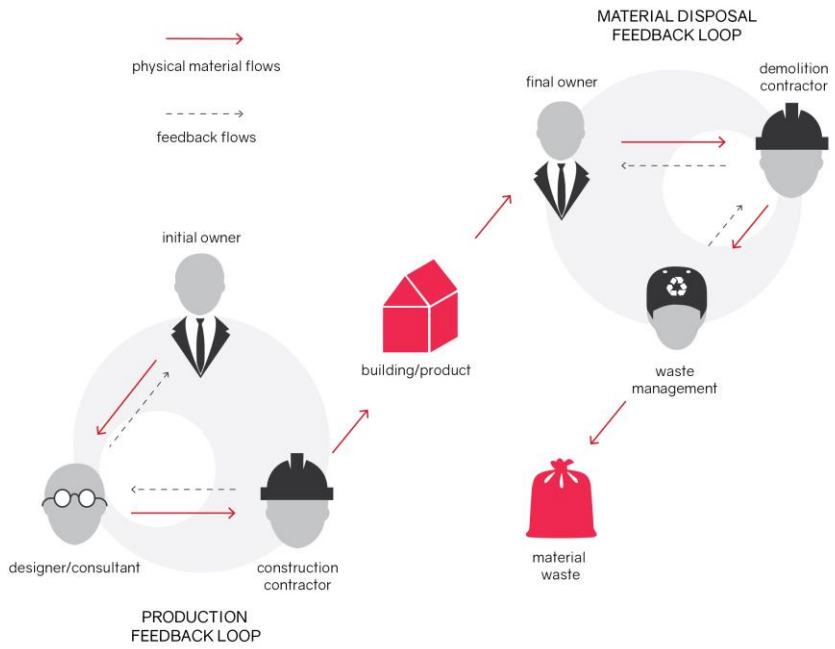


Figure 24: Standard linear material life model, where objects are designed, produced, and disposed of. In this model, the building separates feedback loops in its production (design, build cost, etc) and feedback loops in its disposal (disassembly cost, waste management, etc)

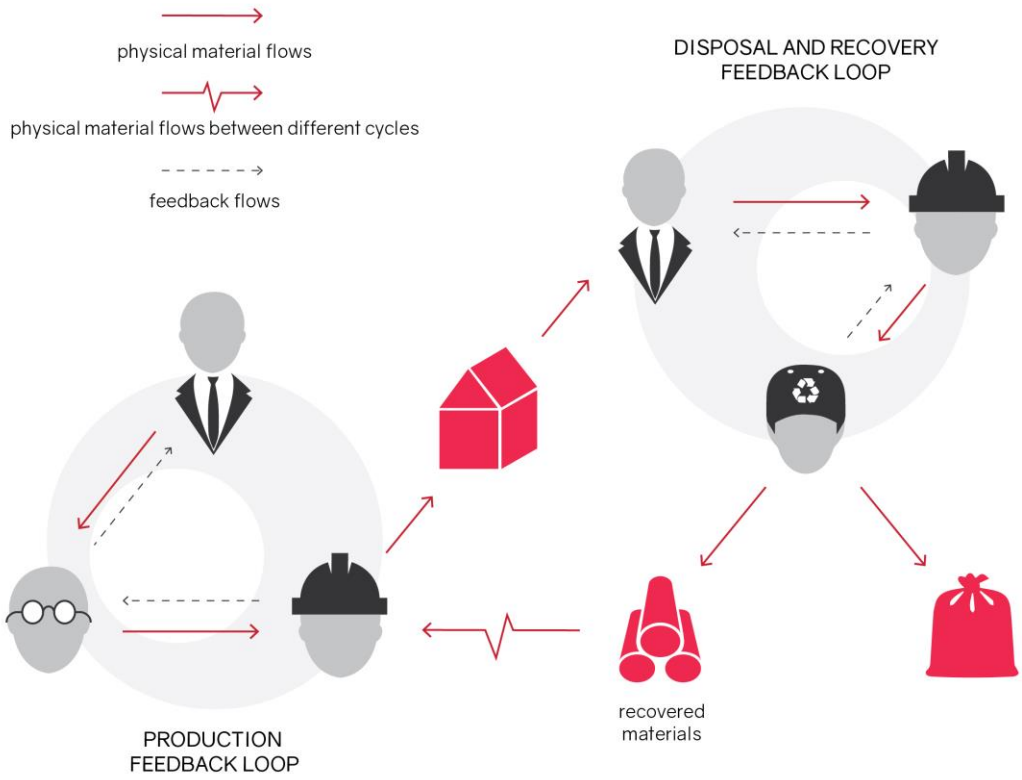


Figure 25: A more modern material life model, in which materials may be recovered from an end-of-life object, processed, and utilized in the production of subsequent objects

3.3.1 Physical contingency in circular design

Through the frameworks of reverse logistics and the Circular Economy, the typically imperceptible event-scales of material lives have gained a medium through which to become tangible design criteria. When end-of-life removal and disposal of objects falls outside the scope of design, the form of an object is primarily concerned with a singular set of performance criteria for it use. This could be criteria such as the ergonomics and aesthetics of a household item or the operational energy and cost of a building, where both cases describe formal criteria specific to the production and use stages of the object. By introducing reverse logistics and material reuse metrics into the initial design process, feedback loops are created between the initial design process and extended event scales of the material life (figure 24, 25, 26). Therefore, Circular Design not only considers the formal performance criteria for the production and use of the object, but can include formal criteria to facilitate the recovery, removal, processing, and reuse of objects and material.

"Design for Recycling" (DFR) was one of the first common strategies in industry to introduce end-of-life formal criteria into product design. This technique is commonly associated with the automotive industry and its treatment of plastics, as their design challenges deal with complex multi-material assemblies on cars that live significantly shorter usable life cycles than their contingent materials are capable of (Maier and Calafut, 1998). As stated by Leterrier (2000), DFR is one of the primary design tools utilized to link conventional design workflows with environmental efficiency over a product's full life cycle. Rosen (1996, p. 1) notes that life cycle issues such as recyclability were conventionally addressed in a "redesign mode" or late design development stage as secondary criteria after primary decisions were made. By employing Life Cycle Analysis (LCA), DFR can develop formal criteria for end-of-life and reuse of objects and materials.

Designing through this strategy involves two key initial areas of consideration: identifying the potential environmental issues that exist with a proposed product and determining how these issues can create direct design criteria for design decision making (Leterrier 2000). Completing these steps involves examining challenges and limitations with the common recycling techniques that will be used to process these products, rather than leaving those decisions to recyclers beyond the design scope (Froelich et al, 2007). According to Ehrig (1992) and Cornell (1995), the three primary methods for plastic recycling are mechanical recycling, chemical recycling, and energy recovery. Based on the European Commission on Environment's (2016) decree that prevention and preparing for reuse are the top two most sustainable recycling options available as they minimize energy addition and waste, mechanical recycling is likely the most efficient and desirable process of the three methods, since it is the closest to preparing materials for reuse without having to fully break them down and reform them.

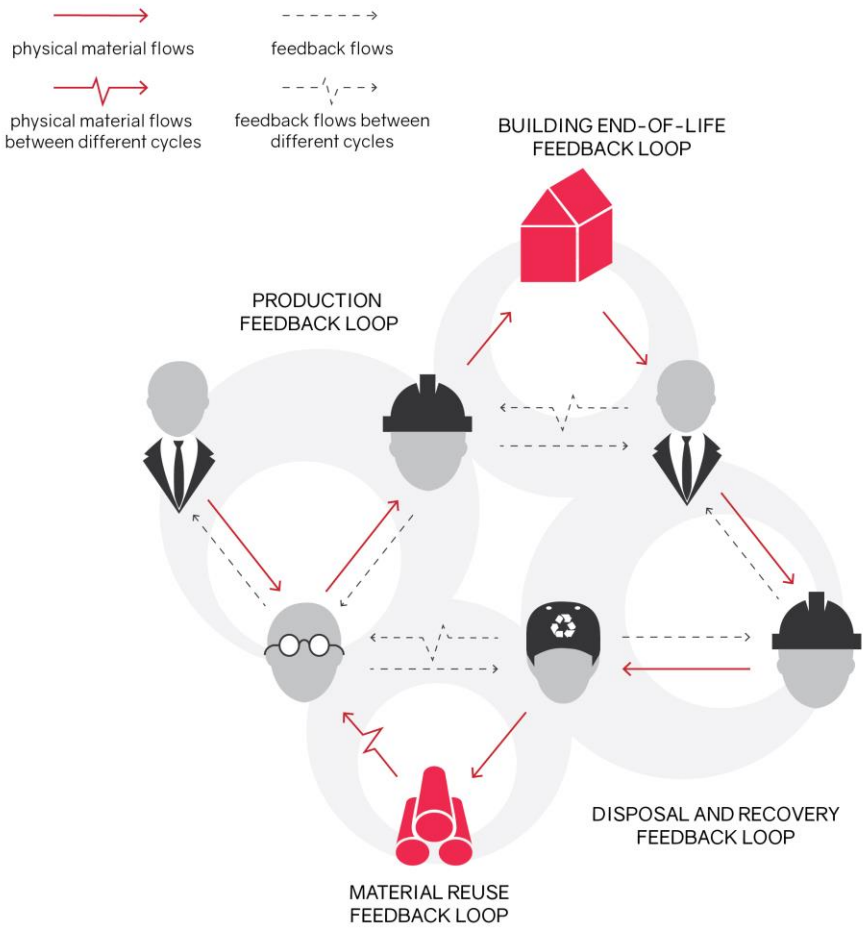


Figure 26: A contemporary circular material life model. Most importantly, this model involves collaboration between design and waste management (in the "Material Reuse Feedback Loop") in order to sync challenges and opportunities between material beginning and end-of-life. Secondarily, demolition costs are factored into project costs, providing a feedback to initial design, and material tracking allows for end-of-life owners to receive feedback from the building's beginning-of-life on how to best maintain, remove, and/or reuse materials (in the "Building End-of-Life Feedback Loop")

To allow for mechanical recyclability of products, the primary identified challenge is the ability to automatically separate and sort different materials using simple mechanical processes (Maier and Calafut, 1998; Froelich et al. 2007). As described by Froelich et al (2007), common separation techniques for plastic recycling in Europe include aerodynamic sorting, electrostatic sorting, and optical infrared sorting. Therefore, factors such as size, shape, and colour design choices can affect their separability. An example of this relationship and its lack of consideration is that car interiors

primarily use black plastics in relatively indistinct geometries, despite that black plastics are impossible to optically differentiate and sort using common infrared systems (Froelich et al, 2007). As a result of this, Froelich et al (2007, p. 903) note that only 3-4% of plastics in vehicles are recycled at their vehicle end-of-life, due to the infeasibility of implementing more complex sorting and separation processes.

Design for Disassembly (DFD) is another key sub-concept in the practice of designing products and materials for recycling. As such, the techniques to design buildings for disassembly are quite similar to those that are used to design products for recycling. As stated by Leterrier (2000, p. 12), the key concept of DFD is the "[separation] of multimaterial products into monomaterial constituents [as] a prerequisite for product life extension, to ease maintenance and repair operations, and also for material recovery into useful applications." As seen previously in DFD strategies, design considerations at this scale can include factors such as the selection of materials to combine into building components and assemblies, the method of combining materials (whether using glues versus mechanical fasteners for example), and the order of combining materials (some materials have higher reuse value, and some have shorter or longer intervals before needing to be replaced). The base concept of Design for Disassembly as a set of design criteria is that it optimizes reverse-logistical constraints of construction material by reducing the time, labour, money, and energy required to recover materials and reuse them, or at the very least to disassemble and dispose of them (Guldager-Jensen and Sommer, 2016). Similar to Design for Recycling, DFD is based on the premise that individual material lifespans are often longer than the use lifespans of the buildings or assemblies they compose, therefore waste is produced when these materials are prematurely discarded without fulfilling their useful energetic and physical potential (Guldager-Jensen and Sommer, 2016). The most common example of this concept in architecture is demonstrated by Duffy (1990) and Brand's (1995) building layers problem, where each discrete physical system of a building (differentiated into site, structure, skin, services, space plan, and furnishings) has a different lifespan. Where the structure and foundation of a building have the potential to last for over 150 years, other layers such as the skin, mechanical systems, and interior furnishings only typically last up to 40 years, 15 years, and 3 years, respectively (figure 28) (Brand, 1995).

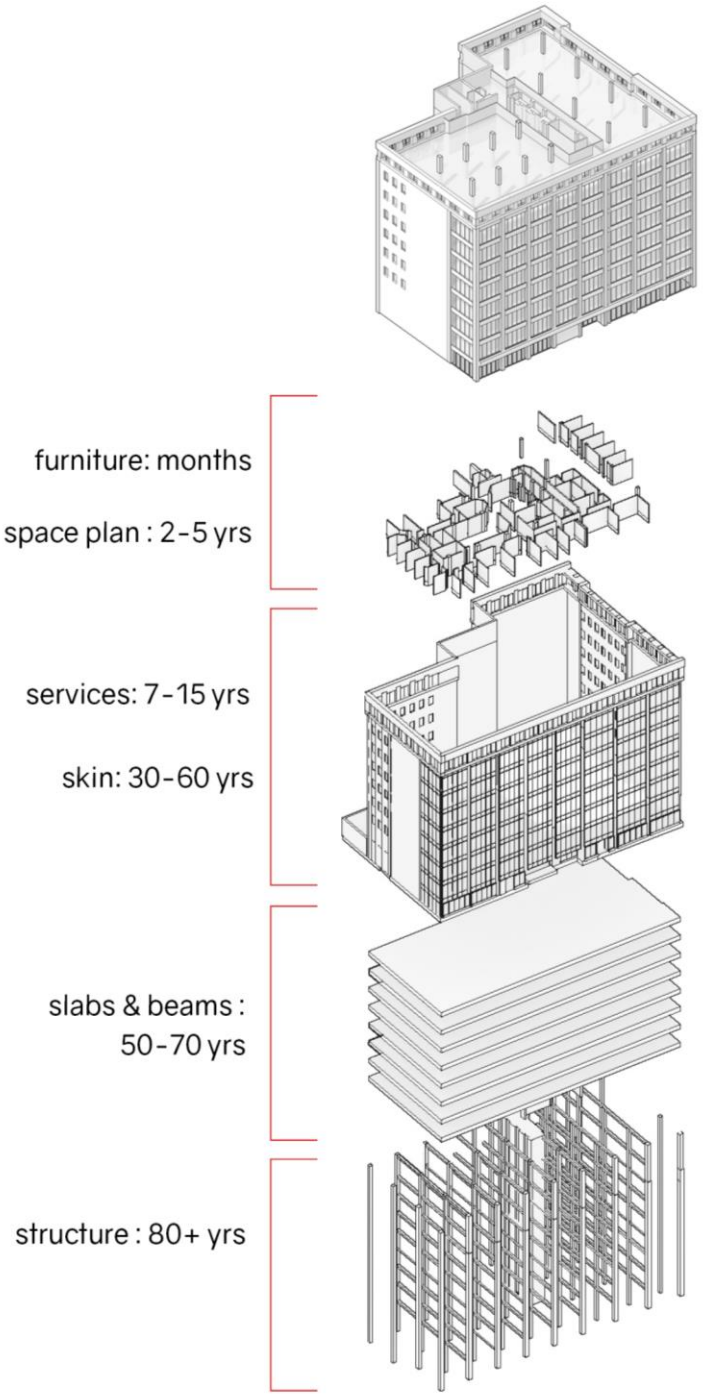


Figure 27: The expected lifespans of different building layers for a 1970s-era downtown Calgary office building (Guldager-Jensen et al, 2019)

A number of studies exist that explore the geometric, material, and tectonic implications of DfR in the design of common objects. One notable example is Umeda et al's 2013 case study of an LCD TV design, in which the recyclability rate of the TV and its component parts is quantifiably linked to various physical design choices. The design methodology utilized by Umeda et al (2013, p. 135) involves developing a geometric product model with specified materials, preparing an end of life scenario for the product, calculating impact and recyclability of the product and its materials, and generating design alternatives based on the analysis.

The findings of this study resulted in a number of proposed physical design changes to the TV to optimize it for recycling. Firstly, a material change of the back cabinet from PC and ABS plastics into steel effectively increased the recyclability rate of this component from 0% to 94% (Umeda et al, 2013). Geometrically, this resulted in the elimination of the fillets on the back cabinet corners, due to the switch from injection moulding to steel stamping as the production process. Furthermore, this material change resulted in the EOL process changing from a selective disassembly and separation to a shredding and separation process. The front frame was also changed from plastic to steel to increase its recyclability by 8.8%, and enabling the removal of shredding from the EOL processing.

The feedback and subsequent adjustments made in this brief case study primarily reach back to late stages of the product's design development process. By the nature of requiring a geometric starting point of predetermined components with limited freedom for geometric adjustment, this study does not overtly seek strong feedback loops that change the inherent design concept and form of the TV itself. However, the resulting physical characteristics of the adjusted TV do suggest the capacity to challenge some base form of the TV as an accepted object typology. By changing plastic with low recyclability rates into steel for the back panel and front frame, the TV becomes over 400% heavier, which represents a significant conflict with the concept of an LCD TV as a visually and physically light object. This example therefore presents additional unexplored potential for how the new physical criteria introduced by recyclability might serve to produce new formal typologies for the object itself.

3.3.2 Economic contingency in circular design

The second form of scalar disconnect addressed through Circular Design is the notion of the changing economic scales over the lifetime of a product. As concluded by Guldager-Jensen and

Sommer (2016), typical design models for buildings (as well as products) only concern themselves with the economics of producing those objects. This includes economics around sourcing material, transporting material, as well as processing and/or assembling it. More advanced models of building production factor the cost of ownership into design bidding and development, meaning that a second broader scale of economics regarding building operation (energy consumption and maintenance for example) is introduced into the design process (Guldager-Jensen and Sommer, 2016). However, by introducing reverse logistics and material reuse into the realm of consideration, the economic scale of design broadens to include factors around object disassembly/removal, material and value recovery, and potential material processing into new material or objects.

In Guldager-Jensen and Sommer's (2016) Circular Design framework, these new economic scales for design are discussed through the notion of designing for the Circular Economy. This design model serves to identify all the possible scales (referred to in the model as "loops") at which objects and materials can be reused, in order to delineate and target the specific economic conditions for each desired level. On one hand, objects can be reused at the smallest scale of their "biological materials", where they are broken back down into energy and/or feedstock input for other processes if there is no more use for them as physical products. Alternatively, objects can be reused at a physical level by either maintaining or upgrading them and reusing them at-scale or breaking them down into their component "technical materials" to be used in producing new material. In this model, the smallest "loops" of material reuse (meaning the closest loops to 1:1 physical material reuse) are the most desirable because they typically require the least amount of input energy and money to achieve in order to produce valuable products again (Guldager-Jensen and Sommer, 2016, p. 218), and are the easiest to address through the design process.

In order to address the broader-scale economics of material end-of-life and subsequent reuse, this Circular Design framework states that it is critical to create economic connectivity between later-stage stakeholders/processes and early-stage design (Guldager-Jensen and Sommer, 2016). As previously stated, traditional design scope ends at the object use stage at the latest, and therefore has no stake or incentive in addressing product reuse economics (such as how easy and expensive end-of-life material is to disassemble, sort, recover, and/or remanufacture). The economics of material recovery and reuse provide a starkly different challenge than production, as it often requires comparable money and labour to collect, sort, break down, and remanufacture objects into typically

lower-value products than it is to produce new ones from raw material (Ellen MacArthur Foundation, "Growth Within," 2015).

One example Beamon (1999) presents to link early and late-stage material economic scales is the idea of "take-back" policies, which can be implemented at the legislative level or at the private business level. "Extended producer responsibility legislation" is one such example, in which object manufacturers legally receive financial responsibility for the collection and disposal of a product at the end of its use life, providing direct incentive to design the object in a manner that minimizes this cost (Subramanian et al. 2009, p. 259). On the private side, some producers have implemented take-back material ownership models in which the buyer may give back the product at the end of its life, or only rents the products (Guldager-Jensen and Sommer, 2016, p. 210). Therefore, in this model, the responsibility for maintaining, upgrading, and end-of-life handling is retained by the producer. The Ellen MacArthur Foundation (2015, "Growth Within," p. 34) refers to these as "performance models," in which the handling and ownership of the physical object is retained with the producer, and the customer only pays for its performance (such as the Philips 'Pay-Per-Lux lighting system, where the amount of light is the performance that a customer pays for, rather than the fixture itself).

Another potential method to connect beginning and end-of-life material economics and create designer/waste management relationships is by designing objects to utilize waste material (Ordonez and Rahe, 2013, p. 113). Beamon's 1999 work provides a set of considerations for designing with waste that center primarily on the "uncertainty associated with the replacement/recovery process (in time requirements, quality, and quantity of returned products, packaging, and/or containers)" (Beamon, 1999, p. 12). Ordonez and Rahe's (2013, p. 114) survey of designers and their experience of designing with waste material also found that the feasibility and yield of creating products from waste was far greater when using carefully sorted, cleaned, and processed waste chosen directly from industrial waste processors, than when using unsorted and unprocessed waste. Therefore, the ultimate cost of utilizing recycled material for a design project will directly depend on the design practices that were applied to that material in its previous use life and how those processes created more or less usable end-of-life material.

Designing with waste materials has the potential to produce a recurring feedback loop into design, by linking the economic value of end-of-life waste material with the economic cost of utilizing reused building material. When waste input material is from consistent and high-quality processing streams, many of the designers in Ordonez and Rahe's (2013, p. 114) study noted that they could

make production cheaper than they could by using virgin material. Consistency in quality and type of waste that is output from processing facilities is related to the material that is brought into processing facilities, and therefore better input material increases the amount of consistent and high quality reused material supply that is available for designers as input material for lower cost (Addis, 2006). As the cost of natural resources and virgin material rises, this economic relationship has the potential to create legible connections between sound beginning-of-life design decisions and the economic feasibility of subsequent production cycles.

3.3.3 Temporal contingency in circular design:

According to Moreno et al (2016, p. 1), object design has been a classically limited-scale practice with a strictly defined time scale of concern, wherein objects are produced, used, and disposed of and design is primarily involved in the time-scale of the first two steps. Alternatively, Circular Design proposes that reverse logistics and material reuse incentivize the involvement of initial object design in extended time scales of multiple material lives. Ordonez and Rahe (2013, p. 113) frame the temporal challenge as "designing for durability," in which designers attempt to address long-term value issues at the object life scale, such as aesthetic and use value shifts or physical degradation. Based on the observations of the Ellen MacArthur Foundation (2015, "Growth Within") and Korhonen, Honkasalo, and Seppälä (2018, p. 43), economic and thermodynamic laws dictate that material reuse will always result in some degree of value loss. Therefore, durability at the object scale is still a key consideration in durability at the material scale in order to better enable distributed permanence of the material by reducing the number and frequency of different use lives the material must fill.

The factor of extended time-scales produces a number of challenges for design. As discussed by Guldager-Jensen and Sommer (2016, p. 128), one of the key issues in object and material durability is the uncertainty and knowledge loss created over their lifetimes. The more time separates the end of a material's life and/or its reuse from its initial design and production, the more likely there will be uncertainty around its composition, quality, maintenance, and overall identity, which significantly hinders its ability to be repaired, upgraded, and/or reused as future material in smaller and more efficient reuse loops. Issues created by longer time scales may include inconsistent access to material information over its life by relevant parties, changing responsibility for care and monitoring of material over its life, and lapses in maintenance (Guldager-Jensen and Sommer, 2016).

This challenge of temporal knowledge loss can be exemplified through Guldager-Jensen and Sommer's (2016) "Material Passport" tool. The Material Passport creates a connection between a physical material and a corresponding virtual database with information about its composition, quality, maintenance, ownership responsibility, safety, and more that is regularly updated. This link can be made through a scannable element (such as an RFID chip) in the material, thus providing easy accessibility to a material archive and/or BIM model for various stakeholders throughout the material production, operation, and removal processes, and permanently linking the physical element and is location to its respective digital database. By integrating this tool in a material at the design stage, the material therefore has the best possible market exposure and reuse potential after its respective object reaches the end of its use life (Guldager-Jensen and Sommer, 2016, p. 128). Material identification such as this is a common theme across currently-employed methods of addressing temporal contingency, as demonstrated in section 3.3.1. Froelich et al (2007, p. 903) conclude that identification of plastic type is a primary challenge in plastic recycling, made challenging in applications such as vehicle parts, which often use the same colour of plastic parts (black) and therefore make automatic infrared sorting by colour impossible. Al-Salem et al (2009) conclude that feasibility of material recycling is based largely on the speed and accuracy of sorting processes. Therefore, it can be extremely beneficial if consistent shapes, sizes, colours, or labels can be used to identify types of material and their properties at the end of their life when there has been significant separation from their original producer.

Further to knowledge loss, the passage of time in object lifetimes creates significant opportunity for contingent cultural and economic factors to affect their value and reuse potential. As such Moreno et al's (2016, p. 7) literature review identifies "product attachment and trust" (exercised through aesthetics, use experience, and personal meaning) have a significant effect on the longevity of a product. As explored in chapter 1 for instance, some theorists propose that the historical relationship between plastic and disposable packaging creates a social expectation that all plastic products (even rigid, high performing products) are not performative or valuable over long periods and are easily disposable (Lynn, 2013, p. 108). This sentiment is echoed by Ordonez and Rahe (2013, p. 113), who acknowledge that design for durability includes "timeless design and how people relate to the product, [which has] a direct effect on how users discard [it]."

3.4 Case Study: Designing Out Waste

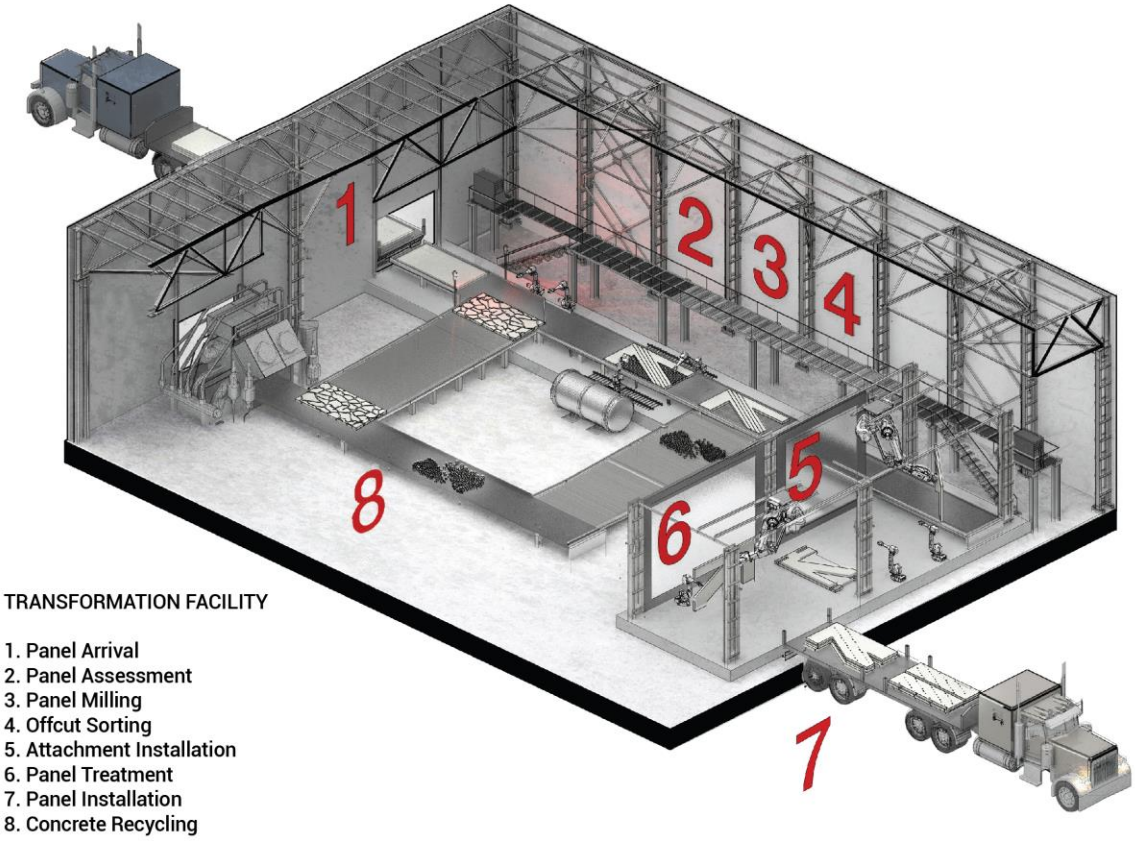
"Designing Out Waste" is a 2019 research publication by Guldager-Jensen et al that explores the synthesis of these three new design scales in a case study redesign of the Calgary, AB Britannia office building. The central premise of this work is that there is a lack of synchronicity between the scales of time, physical form, and economic value of commercial and public building typologies, particularly in volatile markets such as Calgary. The base physical structure and form of these buildings is capable of lasting over 100 years under regular maintenance (Brand, 1995), however the fluctuation of the real estate market can change the economic value and tenant income of these buildings at time scales significantly shorter than 100 years. Furthermore, the typical construction systems of these buildings make them physically un-adaptable to changing demands at the time scale of the market, thus eventually creating significant waste when they prematurely lose value, sit empty, and/or are demolished.

The major strategy used to address this synchronicity problem and link these scales is the robotic refabrication of waste building materials from the demolition of another project into valuable material for the Britannia Building renovation. This approach takes material with a longer potential use life (in this case, precast concrete panels) and transforms it in order to pair it with a building that has a longer potential use life (the Britannia Building), thus addressing each of their value issues and extending the material lives of both. The concrete panel material became waste because it contributed to the antiquated spatial aesthetic (primarily, low light penetration) of the building it cladded, leading to that building's obsolescence and replacement. The Britannia Building became spatial and economic waste because it had a poorly performing envelope and antiquated spatial quality compared to the office market in downtown Calgary. Therefore, the strategy employed in this project targeted new metrics for the material (creating openings for lighting) and for the building (a skin system that was performative, stylistically distinct, and introduced valuable spatial quality). Achieving this required a material processing strategy that would not only minimize the cost and labour to transform the material, however, also have the capacity to directly translate the design requirements of the building into effects for the material.

The method proposed to address both of these requirements was a process termed "robotic refabrication" (Guldager-Jensen et al, 2019, p. 89). This process utilizes an automated production line to evaluate incoming waste building material and ensure its structural integrity, process the material through techniques such as milling to give it new qualities, clean and treat the material, and

prepare the material for installation on a new building by adding new attachment systems (figure 29). Pursuing this method allows production to be economically and logistically efficient, as the facility can be a single point to perform all material processes and only requires minimal paid labour to program the robots. Furthermore, this method also allows the direct and automatic parameterization of building design criteria into milled panel effects, relative to panel locations on the building, panel size, and panel condition. This can be used to create mass customization between all panels, in order to adapt to varying programmatic and spatial requirements (more or less light and privacy, for example) throughout the building (figure 28-29)

Figure 28: The Designing Out Waste proposed concrete panel façade, showing variable aperture for differing programmatic requirements (Guldager-Jensen et al, 2019)



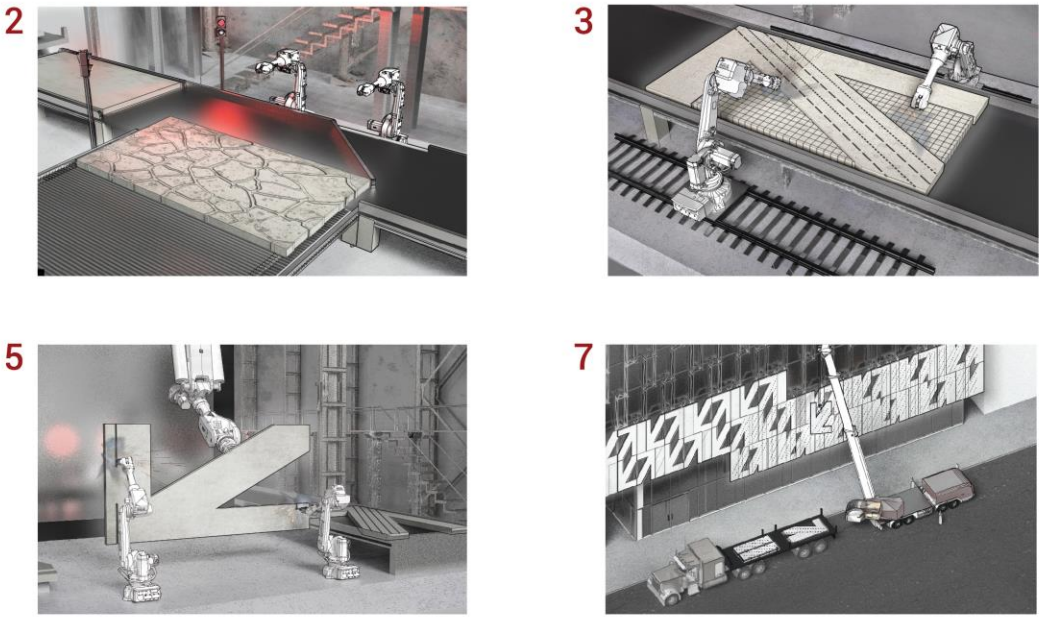


Figure 29: The Designing Out Waste proposed concrete panel refabrication facility (Guldager-Jensen et al, 2019)

3.5 Conclusion

Postmodernist architecture and Bernard Tschumi's concept of the event rejected modernism to establish the precedent for design thinking through broader scales beyond the physical object. The event of the Circular Economy represents the even-further relationship between object design and conventionally imperceptible scales of space, time, and economics across the object lifespan. In order to address these broader issues around reverse logistics and circular material use, circular design must establish tangible links to design through new design criteria for the production of consumer objects and materials, and these new criteria must be specific to the circular diagrams and lifelong events of these objects and materials. Strategies such as designing for disassembly/recycling, material tracking, and designing new circular business models are essential for creating the feedback loops necessary to incentivize these new criteria.

One fundamental area of future consideration suggested through these studies is how the basic accepted typologies of designed objects may change as circular objectives become more tangible and rival conventional design objectives. As exemplified through Umeda et al's (2013) study of TV design for recyclability, circular design criteria often create tension with conventional object design criteria. Challenges around designing for disassembly at the building scale are also exacerbated by conventional architectural object typologies such as conventional composite components, permanent structural connections, and more. These tensions suggest questions around how the form of those objects might respond in the future to compromise between needs of it as a product and as a future reusable material across time and space.

One key outcome that may be discerned from the increasing prioritization of Circular Design criteria is the possibility of the Circular Economy acting as a mental tool to help us virtualize scales of space and time beyond the immediate object, as well as a medium through which to develop new applications of digital design. As stated in a 1954 article by CH Waddington (p. 880), "our mental equipment is not merely one that happens to be reasonably efficient, but it has been shaped precisely to fit the character of those things with which it has to make contact." The lineage of modern design models might suggest a highly literal reading of this passage, wherein any scale of space and time that we cannot immediately "make contact" with becomes something we are unable to virtualize, or think, effectively. This is where digital tools may best be re-instrumentalized in contemporary practice. The ability to virtualize how the condition, performance, and value of material may change over its lifetime based on changing conditions falls squarely within the premise and capability of computational tools such as parametric design and BIM.

Chapter 4

Design Objects for Contemporary Distributed Permanence

According to acclaimed circularity researcher Bradley Guy, "the next generation of buildings will have to express more intentionality of the continuous material cycle" (Wood, 2018, p. 1). While conventional design focuses on the object scale (the "building", as referenced by Guy), the introduction of a material-focused Circular Economy brings into question how our design criteria and processes for objects might fundamentally shift to more closely consider the scale of the material life cycle. The material life cycle prioritizes broader scale challenges such as material recyclability, trackability, divertibility, and embodied energy preservation that are not primary, nor perceptible, in typical object design methodologies. Therefore, this chapter seeks to experiment with basic physical relationships between material design decisions and broader event-scale issues of material and energy in the circular economy.

Current use of digital tools in architecture up to this point has not been able to fully address event-based design scales, however many applications of the tools have shown significant potential to do so, perhaps most clearly evidenced in parametricism (a digital design method that uses parameter-based methods). According to Schumacher (2016, p. 10), parametricism offers the only "answer to contemporary, computationally empowered civilization, and is the only architectural style that can take full advantage of the computational revolution that now drives all domains of society." This promise of parametricism is substantiated by Schumacher's claims that it is the only tool that is powerful enough to address technical functionality of the built environment – structural and material optimization, tectonics, and regional specificity (Schumacher, 2016, p. 10-16). However, these capacities are primarily utilized in the application of parametricism for assemblages (objects), which are defined by Schumacher as having discrete physical form and spatial location (2016, p. 17). This lingering focus on the object-scale of design not only draws parallels back to the design ethos of logical positivism, but perhaps forgets many of the true strengths in the digital-age proliferation of the computer.

Based on Waddington's concepts of tools for thought (1977), we might suggest that true potential of the computer in contemporary design is its ability to perceive, virtualize, and integrate scales of information outside our immediate perception. These scales are described by Waddington's *Problematique* concept, wherein problems become so interconnected and so distributed over time and space that they become impossible to perceive without cybernetic tools through which to do so (1977, p. 8). The Problematique presents itself as a two-part problem for achieving event-scale design. Part one of this problem involves the scaling up of virtual models to consider broader scales

of information (for example, embedding building end-of-life time scales into BIM models) to draw from, while part two involves the parameterizing and spatial organization of that data into materials and objects. Considering these two definitions and the scope of the document, chapter four explores the second definition in determining how broader objectives of the circular economy might be formalized into materials and objects more directly through contemporary design and fabrication processes.

The process in question that will be utilized in this pursuit is robotic additive manufacturing (AM), which offers significant potential as mediums for this new approach to design due to its high degree of digital control and expanding material selection. As explored by various researchers such as Garcia and Retsin (2015), Huang (2016), and Anton and Abdelmahgoub (2018), AM introduces a new form of digital craft that moves beyond mass material standardization to express more specific requirements of object design. Particularly with materials such as thermoplastics (the material used in this chapter's experiments) that have high performative and reuse potential and high embodied energy content, reverse-logistical factors are becoming a primary design priority and a significant motivator for new forms and new fabrication techniques. The ability to directly control material quantity, fabrication time, and logistics at the material scale enables a high level of material specificity that can acknowledge the unique requirements of each material's life cycle and supply chain.

The capacity of these new AM models to reframe object design around broader contextual parameters such as embodied energy and supply chain consistency is not only one of their main strengths in addressing material specificity, but also one of their main hurdles in gaining widespread industry acceptance. The design and optimization of toolpaths are a critical factor in reducing waste (in terms of material, time, and money), but only a small amount of literature exists to delineate basic design principles for AM in solid architectural components. Particular consideration is needed into the potential of various emerging techniques to improve the efficiency and control of AM fabrication and design in architectural contexts. This chapter therefore tests and synthesizes several approaches to large-scale robotic AM in order to explore how the design of architectural objects might better tackle circular parameters of material and energy reduction in their production.

Figure 30: A rendering of the Edmonton Lab Hub project by DIALOG Design (2019)

4.1 Case Study Project: Edmonton Lab Hub

The Edmonton Lab Hub (ELH) was an Alberta Public Health project that intended to amalgamate most of Edmonton's disparate clinical laboratory facilities into a single building with programs for office space, automated sample processing, and lab testing. In the winter-spring of 2019, the ELH project was in its later design development stages, part of which involved resolving and detailing the aluminum façade panel cladding system. Based on the conceptual design of the building as a series of folding layers, this façade system features a series of non-orthogonal surface tessellations and angled reveals for windows and other details (Figure 30). As a result of their geometry, as well as the technical cladding requirements for the building, this façade system creates a high level of material and tectonic complexity, requiring a significant amount of material and energy to construct (Figure 31).

The ELH façade system has been selected as a baseline case study for a series of experiments that explore the potential of digital fabrication (specifically additive manufacturing) to achieve higher design specificity and circular potential in building material. As suggested, the geometric effect on the façade panels in this project is specific to the anticipated use and character of this building over its life. However, this more specific geometry also requires greater energetic and material input due

to the extra labour and complexity in folding and supporting the panels, as well as creating eventually less circular end-of-life materials due to the greater challenge of removing and disassembling this system when compared to standardized and simpler façade cladding. Therefore, design problems such as this have the potential to demonstrate the merits of digital processes such as additive manufacturing, which can increase customizability and specificity of systems without significantly increasing material complexity or labour due to the direct translation from digital program to physical production.

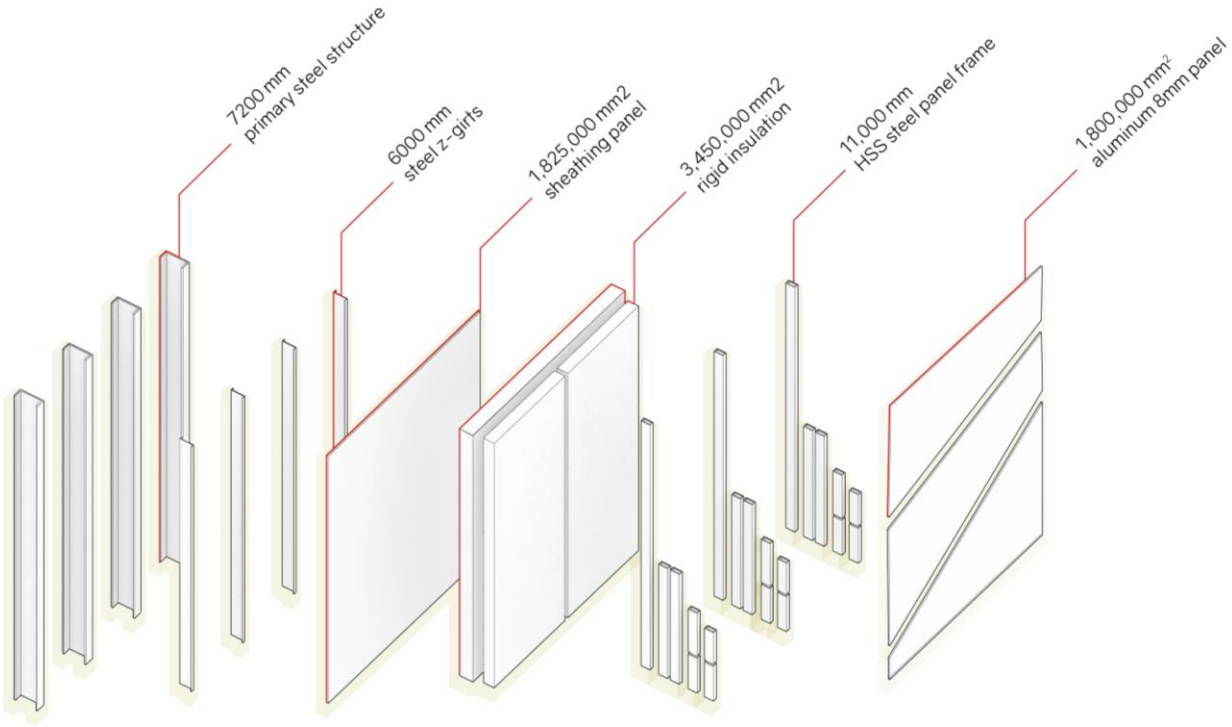


Figure 31: The material complexity required for a square profile panel from the ELH facade

This chapter uses the square-profile panel shapes from the ELH façade at varying small scales as a baseline for scalar and volumetric goals of a series of 3D printed geometries (Figure 32). The 3D printing experiments consider how to produce geometry with these standard cladding requirements (containing certain volumes and covering certain surface areas) while minimizing energetic, material, and labour input by exploring the efficiency of various shapes, surface textures, and fabrication control variables. Furthermore, based on the previous discussions of wasteful plastic lifespans, this

chapter also discusses a select number of supply chain implications of using and reusing plastic in this 3D printing process for architectural components.

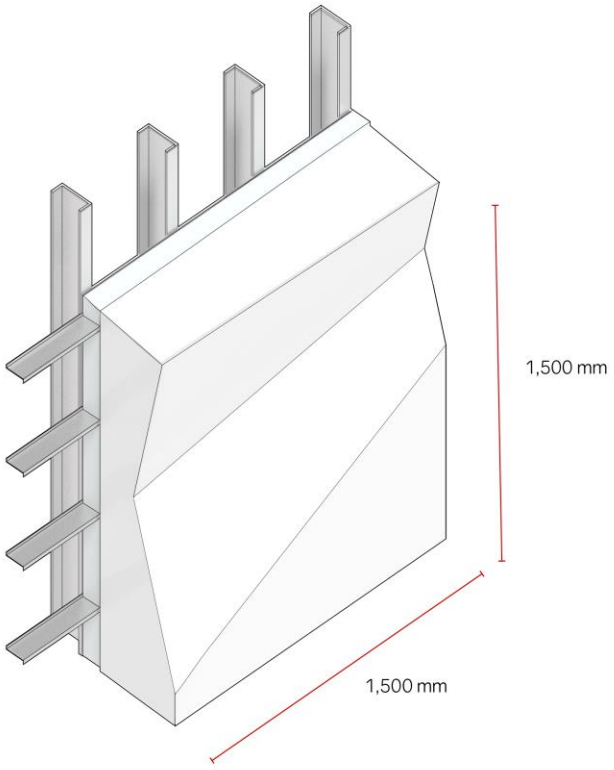


Figure 32: The case study panel profile used as a baseline for the 3D printing experiments

4.2 Key Circularity Metrics for Plastic-Based Additive Manufacturing

Contemporary circularity research urges the consideration of material-specific design criteria in order to address the reusability and optimization of various resources and applications (Umeda et al, 2013). Thermoplastics (used both in AM and in other applications) are a unique material that is long-lived, highly performative, and potentially infinitely remouldable with little energetic input, thus offering the potential to reduce the need for new material production. However, in practice, plastics are usually limited to life in a single building or product (Geyer et al, 2017) and the mechanical recovery rate of plastic in the building industry generally falls below 30% (Plastics Europe, 2019), compared to the recovery rate of steel at over 95% for the building industry (Bowyer, 2015, p. 3). A review of literature on recycled material in construction identifies three key areas of challenge: economics of material processing, the procurement and supply chain model for sourcing recycled

products, and the value of the final recycled product for the industry. The first area of concern stems from the economics of recycled material. Taking plastics as an example due to their durability, resin prices for the most common building plastic, PVC, are currently sitting between 22 and 28 cents (USD) per pound (Plastics News, 2019), representing a fourfold decrease from the price of virgin PVC resin at between 90 and 110 cents per pound (Plastics News, 2019). For comparison, the cost differential for aluminum is under a threefold difference of between 30-40 cents for recycled material (Infomine, 2019) and 80-90 cents for raw material (figure 4) (Capital Scrap Metal, 2019), contributing to higher reuse rates. Despite the typically low cost of recycled resin, Addis (2006, p. 55) notes that the sourcing of reused materials involves additional concerns that can make it significantly less viable and appealing for both producers and builders. On the production side, disposed material must be collected from site, sorted, cleaned, ground, and re-extruded, which often also requires transfer to different facilities, thus incurring significant costs and driving up the price of recycled products (Al Salem et al, 2009). On the construction side, additional unforeseen costs may include researching and identifying suitable material in end-of-life buildings, ensuring that these buildings are disassembled in a way that preserves these materials, and testing materials to prove their performance (Addis, 2006, p. 24).

Table 1: Price indices for two common types of virgin and recycled plastic compared to those of aluminum (InvestmentMine, 2019)

	Virgin Price Index	Recycled Price Index
PVC	$ .90 – 1.10 /lb	$ .22 – .28 /lb
HDPE	$ .36 – .42 /lb	$ .14 – .17 /lb
Aluminum	$ .80 – .90 /lb	$ .30 – .40 /lb

Contemporary models of AM with thermoplastics offer an opportunity to address this challenge of the supply chain by relying more on geometry for performance, and thus reducing the complexity of material relationships. Guldger-Jensen and Sommer's (2016) standards of designing for disassembly state that higher simplicity of building components makes them easier to maintain and reuse (p.46). This includes avoiding non-separable connections (such as composite plastics), relying more on individual specialized components over compositions of different elements, and using modular elements that can easily be replaced (Guldager-Jensen and Sommer, 2016, p.47). Therefore, the experiments in this chapter seek to demonstrate the ability to perform some simple functions (such

as enclose volume and create surface effects, as the ELH panels do) with single geometries that use a single material, as compared to the case study panels that use multiple materials.

The second area of challenge is in the procurement and supply-chain model for sourcing and producing custom plastic recycled components. According to Addis, the key challenge for procurement models of recycled materials is in availability and consistent supply of products, which is more challenging to guarantee due to greater uncertainty in this supply chain (2006, p. 24). Where conventional building products can be produced to-order, the reused product supply consistency relies on questions such as the availability of materials in existing buildings, the disassembly process of those buildings, and the quality of materials in those buildings (Addis, 2006, p. 24). Therefore, as opposed to a standard design process where materials and goods are purchased after final specification in the project, the use of reused materials requires much earlier identification of potential suppliers and order of products (Addis, 2006, p. 34). This also creates greater strain on the project team, as earlier material ordering requires earlier integration and earlier completion of work between disciplines with interrelated design concerns (for example, ordering material for the building cladding requires earlier resolution of the structural grid and envelope design).

To address this second area, the metric of material consumption in the experiments has been identified as central for gradually increasing the feasibility of plastic reuse and gradually promoting its circularity. By developing AM strategies to reduce the material input for new materials, these experiments argue that the significant labour, cost, and energy involved in sourcing existing material can be reduced. A reduction in these logistical and energy-intensive processes also has the opportunity to address the first key plastic reuse challenge of cost-benefit issues. Therefore, both direct material consumption and resulting embodied energy are used as key metrics for these experiments in order to both address added costs and material, and to make an energetic comparison against the ELH panels.

The third critical area for recycling feasibility, and the one in which architecture has the most agency, is the type of product being produced from recycled material and how this affects the value potential and incentive for recycling material. For example, virgin plastic sees significant technical value in performative applications such as vapour barriers and piping (Van Uffelen, 2008, p. 6), however stricter technical requirements for these applications make it challenging to utilize recycled content, due to its inconsistent purity (Addis, 2006, p. 166). Therefore, reused material has to compete with

other more established new building materials such as woods for similar roles, while often failing to offer a significant discount due to the added costs of processing and re-fabricating recycled content.

Figure 33. The Durotaxis Chair, exemplifying Alvin Huang's notion of "designing a 3D print" by considering toolpath sequence, thickness as related to structural requirements, and material gradient (Huang, 2016)

In addressing this third challenge of plastic reuse incentive, Bell (2013) notes the importance of affective material specificity in tackling aspects such as cultural value of material through its form and character as a strong tool for improving material value. This issue might be extended to the use of AM in architecture as well, where true value and acceptance are not in recreating existing forms with different material and techniques, but creating qualitatively new forms through processes that greater consider broad design events. Therefore, there is a critical opportunity to explore how new broader design scales and fabrication techniques might express themselves through material in new affective ways that also reinforce their various circular and other performative goals.

Therefore, a final mode of discussion and evaluation for the experiments in this chapter is Alvin Huang's notion of "designing a 3D print, rather than 3D printing a design" (Huang, 2016, p. 318).

This idea may be seen as emblematic of event-focused approaches to design, as it discusses the need for physical form to be driven by the capability of its distributed processes, rather than vice-versa. However, in relation to the plastic reuse problems posed by Bell (2013), this approach suggests the opportunity to explore new affects in fabricated materials. As per Sadalla and Sheets' (1993) observations on cultural and social value of material, the experiments in this chapter lastly aim to explore new material aesthetics offered by the strengths and capabilities of the 3D printing process. Ultimately, in unison with comparisons from the previous two metrics, this will aim to demonstrate both the affective and effective potential of producing customized material geometry through robotic AM.

Facades present a strong territory for this exploration for several reasons. Perhaps most significantly, in relation to Bell's (2013) discussion of affective specificity, Gruber and Gosztonyi (2010, p. 503) state that the façade defines the architectural character of the building and its interface with the public, and places strong emphasis on affective performance alongside its technical requirements. Furthermore, according to Brand (1995), facades present a lifespan of at least 20 years, or less than half the average building lifespan according to O'Connor (2004), thereby reducing their durability-based material burden in comparison to layers such as structure. Therefore, the façade also presents special stakes for optimizing circularity in terms of material choices and fabrication techniques – presenting a strong testing ground against which to evaluate the effectiveness of new additive manufacturing techniques.

4.3 Methods

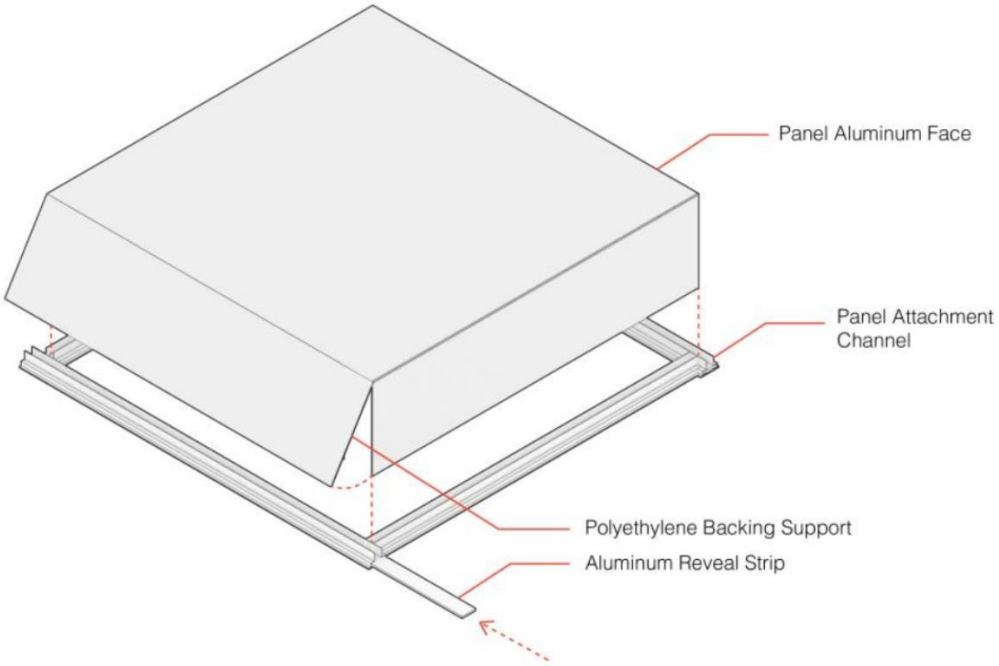


Figure 34. Sample 500 x 500 x 150mm standard panel geometry volume in context with conventional attachment channels

4.3.1 Baseline Model Calculations

The base model selected for comparison is the square profile panel used in the ELH case study, scaled down to 500mm x 500 mm x 150mm for easier iteration and comparison (figure 34). The panel in question uses a pure aluminum sheet configuration measuring 3mm thick, however many of these panel systems use a laminated configuration with 1mm of aluminum sandwiching 2-5mm of polyethylene (PE) core, therefore both will be considered in embodied energy calculations. A digital model of the panel system was created to measure material quantities and provide the embodied energy of this system as a baseline to test against material and energy from the various optimization strategies. A simple formula for calculating embodied energy of material is derived by calculating material volume in m^3 from the 3D model, converting it to weight by multiplying it with its material density in kg/m^3, and then multiplying its weight by its suggested embodied energy factor (measured in MJ/kg) to obtain its energetic footprint in MJ:

Energetic Footprint in MJ
= (Volume in m3) (Material density in kg/m3) (Embodied energy factor in MJ/kg)

The single-sheet 3mm thick common aluminum panel (with a volume of .0085m^3 and an aluminum material density of 2800 kg/m^3) results in an embodied energy figure of over 4500MJ when factoring Chen et al's (2001, p. 328) suggestion that aluminum's embodied energy is 191 MJ/kg:

(0.0085m^3) (2800 kg/m^3) (191 MJ/kg)
= 4500MJ Energetic Footprint for 3mm Aluminum

Alternatively, the sandwiched polyethylene panel with 1mm of aluminum and 2mm of PE yields 935g (0.00935 m^3) of polyethylene material. Using a density figure of 900kg/m^3 and an embodied energy factor of 60 MJ/kg (Ashby, 2012, p. 505) for PE yields approximately 505MJ of embodied energy for virgin material. In addition to 1mm of aluminum panel at 1500MJ of energy, this equals approximately 2005MJ of embodied material energy for the composite panel:

(0.00935m^3) (900 kg/m^3) (60 MJ/kg) = 505MJ Energetic Footprint for 2mm Polyethylene
+ (.0.0028m^3) (2800 kg/m^3) (191 MJ/kg) = 1500MJ Energetic Footprint for 1mm Aluminum
= 2005MJ Total Energetic Footprint for 1mm Aluminum Panel w/2mm Polyethylene Backing

It was important to also consider metrics of fabrication and disassembly potential for embodied energy implications of this system versus the case studies. As Guldager-Jensen and Sommer (2016, p. 77) suggest, material lamination in fabrication prevents separation and thus reuse of any component materials at the end of their product lives. Little research currently exists to directly quantify the embodied energy implications of laminates versus monomaterials, however we can propose the embodied energy input of virgin and recycled material as a method of demonstrating energetic consequence for disposing instead of reusing aluminum and PE material. As stated by Chen et al (2001, p. 328), the embodied energy input required for raw aluminum is 191 MJ/kg, versus 8 MJ/kg for recycled material. For polyethylene, according to Ashby (2012, p. 505), virgin

material measures between 80 and 115 MJ/kg, and recycled material between 45 and 55 MJ/kg. Therefore, referring back to our baseline panel, the embodied energy required to produce a new 3mm aluminum panel from recycled material is 190MJ, 96% less than the 4500MJ cost for a new panel:

$(0.0085m^3)$ $(2800\ kg/m^3)$ $(8\ MJ/kg)$
= 190 MJ Energetic Footprint for 3mm Recycled Aluminum

Therefore, we might conclude that the laminate composite panel at 1970MJ may also include an energetic cost add of 4310MJ (4500MJ – 190MJ) as a penalty for making material non-recyclable for the production of subsequent panels.

4.4 Digital Simulation Experiments

Figure 35. Robotic printing of recycled plastic on a 45 degree MAAM slice angle from the "Print Your City" project (photograph by The New Raw, 2018)

4.4.1 Toolpath Orientation Optimization

One of the main significant challenges in printing volumetric closed forms such as the panels seen in the ELH project is the need for support material in order to print high walls and ceilings. The angled printing technique demonstrated in the "Print Your City" project by The New Raw laboratory (2018) in Thessaloniki poses an opportunity to address this issue. By using a robot arm to deposit material at a non-orthogonal 45 degree angle, this strategy produces a series of contoured toolpaths that reduce the need for additional structure or support to achieve volumetric forms (figure 35), a technique referred to by Isa et al (2018, p. 1637) as Multi-Axis Additive Manufacturing (MAAM) in their evaluation of toolpath orientation. MAAM refers to the contour plane for toolpath layering as the "slice angle," wherein the optimal slice angle identified to produce overhanging geometries without support is 40 degrees,

which minimizes the two main failure types of collapsing failure and adhesion failure (Isa et al, 2018, p. 1640).

This exploration first applied this slice angle to the basic panel cuboid in digital space, with an assumed material deposition size of 3mm (using a similar Fused-Deposition style larger extruder nozzle as in the "Print Your City" project), which yielded a toolpath length of about 312m. Compared to a shell with a braced truss-style support system, the single-shell toolpath resulted in over an 80% decrease of total toolpath length to produce this geometry. This toolpathing strategy was then applied to a variety of geometric primitives alongside standard orthogonal toolpaths in order to compare the length efficiency of each.

Table 2. Toolpath length and volumetric efficiency for basic primitive geometries with orthogonal slice planes and 40 degree slice planes

	Orthogonal Toolpath Length	40 Degree Toolpath Length	Toolpath Type Length Efficiency Difference
Hexahedron	719 m	571 m	26% gain
Cylinder	566 m	451 m	25% gain
Half-Sphere	364 m	330 m	10% gain
Truncated Cone	317 m	277 m	14% gain
Tetrahedron	247 m	212 m	16% gain
Octahedron	127 m	163 m	22% loss
Dodecahedron	113 m	109 m	3% gain
Icosahedron	122 m	123 m	1% loss

One downside observed in the single-shell printing technique from The New Raw (2018) is the extrusion thickness required for material deposited to maintain a single shell structure, which has a significant effect on the print time and material volume required. Printing of our 600x600x150 panel geometry with an approximated shell thickness of 6mm yields a required material volume of 4350 cm^3, which translates to over 4kg of HDPE filament (approximately four standard commercial filament rolls) based on Baechler et al's (2013, p. 120) conclusion that recycled HDPE holds a density of approximately 950kg/m^3. For this 4kg of HDPE material, according to Ashby (2012, p.

505), the embodied energy is estimated at approximately 105MJ for recycled material (compared to between 400 and 444 MJ for virgin material).

4.4.2 Geometric Primitive Optimization

The slice plane angling experiments by Isa et al (2018) suggest that there is also potential for geometric optimization to optimize performance and toolpath lengths for various volume and dimension-based objectives. Therefore, this work compared orthogonal toolpaths against 40-degree toolpaths on a selection of single-layer closed shell simple geometries that were fit to a 600 x 600 x 150mm bounding box with assumed 2mm contour increments, in order to suggest optimal forms to reduce length and material for various objectives.

Table 3. Volumetric efficiency for basic primitive geometries with orthogonal slice planes and 40 degree slice planes

	Shape Volume within Bounding Box	**Shortest Toolpath Length**	**Length-per-Volume Shape Efficiency (using most efficient slice plane)**	**Proportional Variance on Toolpath Length Efficiency**
Hexahedron	.05 m^3	719 m	14,380 m/m^3 11,420 m/m^3	Taller shapes yielded slightly reduced efficiency (>5% for 100% height add), whereas shorter shapes were increased (<5% for 50% height decrease)
Cylinder	.084 m^2	566 m	6,738 m/m^3 5,369 m/m^3	Taller shapes yielded slightly reduced uniform efficiency (>5% for 100% height add) , whereas shorter shapes were uniformly increased (>5% for 50% height decrease)
Half-Sphere	.056 m^3	364 m	6,500 m/m^3 5,892 m/m^3	Taller oblong shapes yielded higher efficiency at a non-uniform rate (7% gain for 100% height increase, 9% for 200% height increase)

	Shape Volume within Bounding Box	**Shortest Toolpath Length**	**Length-per-Volume Shape Efficiency (using most efficient slice plane)**	**Proportional Variance on Toolpath Length Efficiency**
Truncated Cone	.035 m^3	317 m	9,057 m/m^3 7,914 m/m^3	Taller cones uniformly increased efficiency (15% gain per 100% height add), where shorter cones uniformly reduced efficiency (15% loss for 50% height)
Tetrahedron	.022 m^3	247 m	11,227 m/m^3 9,636 m/m^3	Taller cones slightly increased efficiency (<5% gain per 100% height add), where shorter cones reduced efficiency (10% loss for 50% height)
Octahedron	.018 m^3	127 m	7,055 m/m^3 9,055 m/m^3	Taller shapes significantly improved efficiency (34% gain per 100% height), shorter shapes significantly decreased efficiency (34% decrease)
Dodecahedron	.013 m^3	113 m	8,692 m/m^3 8,384 m/m^3	Taller shapes improved efficiency (11% gain per 100% height), where shorter shapes significantly decreased efficiency (27% loss per 50% height)
Icosahedron	015 m^3	122 m	8,133 m/m^3 8,200 m/m^3	Taller shapes improved efficiency (15% per 100% height) while shorter shapes decreased efficiency (15% reduction for 50% height)

After determining the single-objective optimization of each shape for volume or toolpath length, the volumetric efficiency and two-dimensional efficiency were each remapped onto a scale between 1 and 8 between the maximum and minimum values obtained in these tests, then averaged to determine the most optimal shape to meet both objectives. Based on this calculation, the most

materially-optimized shape for both volume and dimension was the octahedron by a slight margin, followed by the dodecahedron in second and the icosahedron in third. The least efficient overall shape was the hexahedron, and second least was the tetrahedron.

Table 4. Multi-objective weighted scores and rankings for material optimization of each shape volumetrically and dimensionally

	Weighted Path Length Score (out of 8)	Weighted Volumetric Length Efficiency Score (out of 8)	Ranking
Tetrahedron	3.8	2.1	7
Hexahedron	1.0	1.0	8
Octahedron	6.7	4.8	1
Dodecahedron	8.0	3.2	2
Icosahedron	7.0	3.5	3
Cylinder	1.4	8.0	4
Half-Sphere	2.2	6.8	5
Truncated Cone	2.7	3.8	6

4.4.3 Toolpath Pattern and Thickness Optimization

One critical downside observed in the single-shell printing technique from The New Raw (2018) is the extrusion thickness required for material deposited to maintain a single shell structure, which has a significant effect on the print time and material volume required. In their Acadia 2015 paper exploring large scale 3D printing, Garcia and Retsin demonstrate the ability to 3D print ABS plastic at a 6mm extrusion thickness, while utilizing two air nozzles mounted on the print head to produce faster material cool down to allow deposition of unsupported members.

Printing of our 600x600x150 panel geometry with a solid shell thickness of 6mm yields a required material volume of 4350 cm^3, which translates to over 4kg of HDPE filament (approximately four standard commercial filament rolls) based on Baechler et al's (2013, p. 120) conclusion that recycled HDPE holds a density of approximately 950kg/m^3. For this 4kg of HDPE material, according to Ashby (2012 p. 505), the embodied energy is estimated at approximately 105MJ for recycled material

(compared to between 400 and 444 MJ for virgin material). Even at an extreme extrusion thickness of 6mm, therefore, the fabrication of this component represents a fourfold estimated decrease in raw embodied energy when compared with the laminated aluminum and polyethylene panel assembly (while being fully reusable), and a twelvefold decrease from the purely aluminum panel.

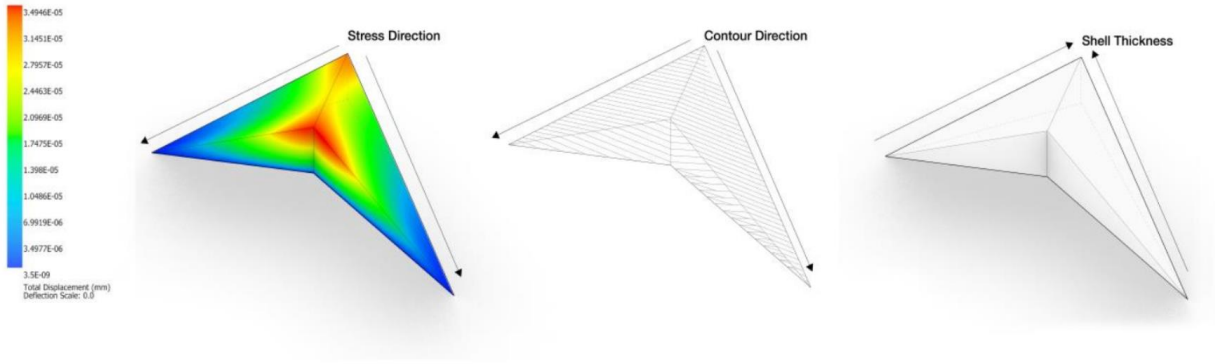


Figure 36. Stresses in the seven-sided geometry producing contour slice planes and variable shell thickness

Because octahedral geometries had the highest overall volumetric and dimensional efficiency and angled contour slice planes oriented closer to the face normals of angular geometry were more efficient, a primitive panel shape was developed and sliced with an angled toolpath direction. This strategy was based on Hernandez et al (2016, p. 947) who observed that compressive strength of printed ABS plastic is consistently higher than its tensile strength, and that strength is higher when compressive forces are oriented in a perpendicular direction to forces exerted onto printed material layers. This toolpath direction was therefore generated by obtaining the principal stresses on the form in order to align these stresses along the compressive axis of the contoured layers (figure 32). Furthermore, the shell of the form was variably thickened in order to obtain higher structural performance in higher-stress areas with longer spans and minimize material in the tip regions where stress and span are minimal (figure 36).

Finally, in order to reduce the material requirements of solid deposition and the toolpath requirements of full contouring of shell thicknesses, this exploration deployed and compared three common waveform contouring strategies that seek to achieve structural shell thickness while minimizing material. More physical testing is required to determine structural performance of these methods, however this test allowed us to compare their performance by toolpath length, showing

that the square wave was the most materially efficient at this frequency of contouring and curve division.

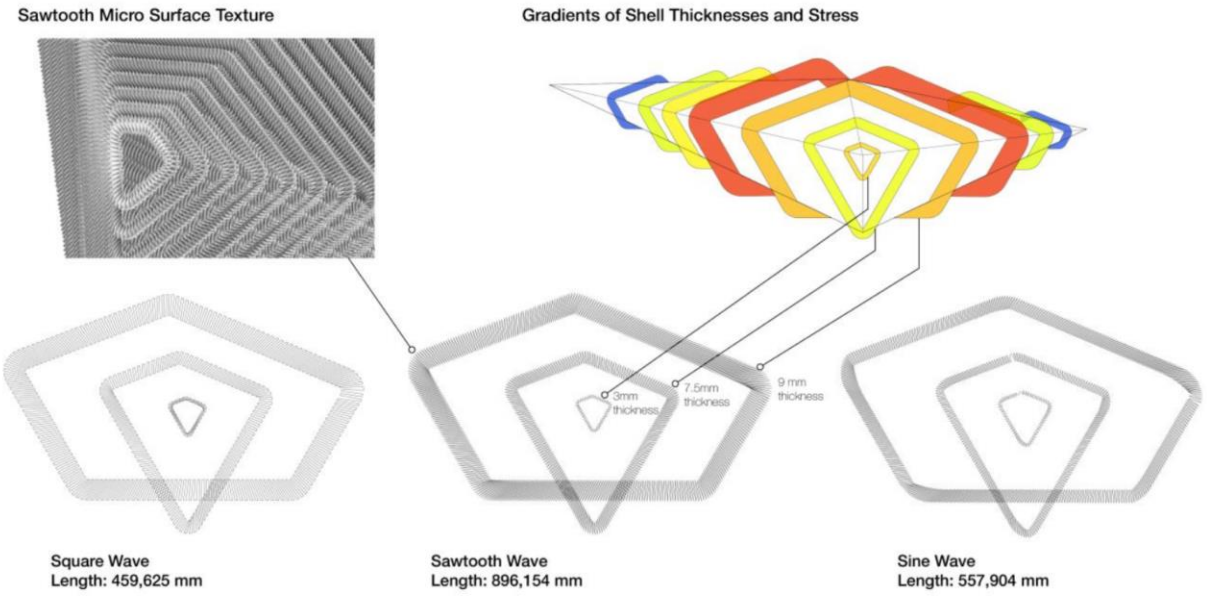


Figure 37. Comparing toolpath length of the variable-thickness geometry using three common waveform patterns

4.4.4 Modularity and Nesting Optimization

Based on the suggestive geometric techniques presented in the previous two precedent studies, this experiment developed a series of nesting iterations using a mix of geometry within regular square façade areas. These tests compare various non-regular component morphologies and organizations at part-to-part scales and part-to-whole scales against conventional panels in terms of toolpath length and efficiency. Furthermore, based on the material circularity principles by Guldager-Guldager-Jensen and Sommer (2016), this work introduced the number of parts required for the grid cell as an additional metric. This number is weighted against our toolpath efficiency in order to consider the benefit of using a higher number of small, modular pieces that are more easily reconfigurable and replaceable, rather than fewer specialized pieces.

The results of these comparisons support the conclusions of the previous geometric studies, where the toolpath scale efficiency on a piece-to-piece basis of the proposed panels is on average approximately 25% more efficient than square panels to cover the same surface area (figure 38). The greatest efficiency increase between the same number of panels was observed for the final iteration, which used two five-sided modified pyramid shapes.

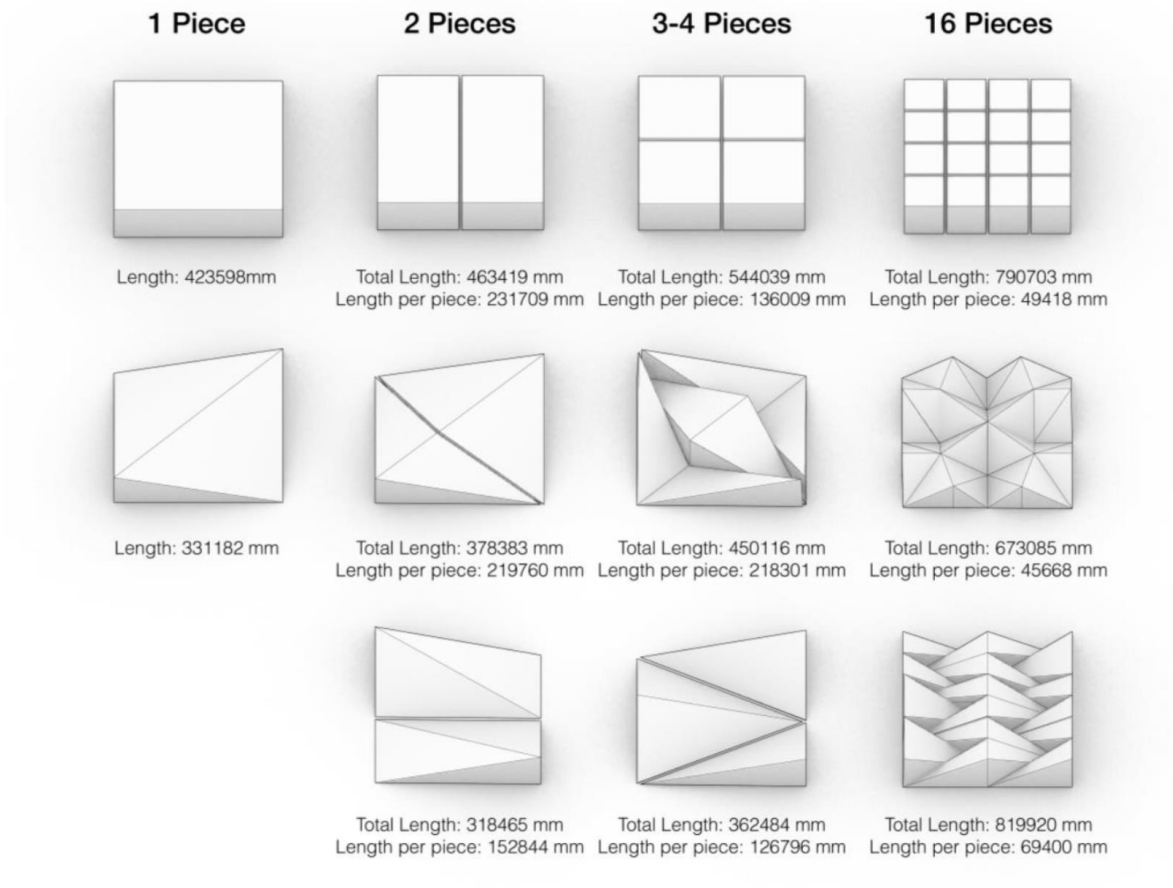


Figure 38. Matrix of pattern nesting tests for angular geometry within a regular square façade area

4.5 Physical Fabrication Experiments

Building upon the findings of the previous digital design experiments section, the digital fabrication experiments attempted to, firstly print a number of test panel iterations from the previous section, and secondly these prints to identify some basic material challenges inherent to standard 3D printing processes, that could then be addressed using robotic 3D printing techniques. Two key challenges were identified in the standard 3D printing process to be addressed using robotic techniques. The first challenge was reducing the support material required to produce overhanging, non-orthogonal, and thick-shelled geometry, by testing waveform shell patterns and non-flat base geometries to print onto. The second challenge was to induce variability within the prints in order to address specific areas that require more or less material and precision, as seen in the surface failures of the standard ELH panel print (figure 39).

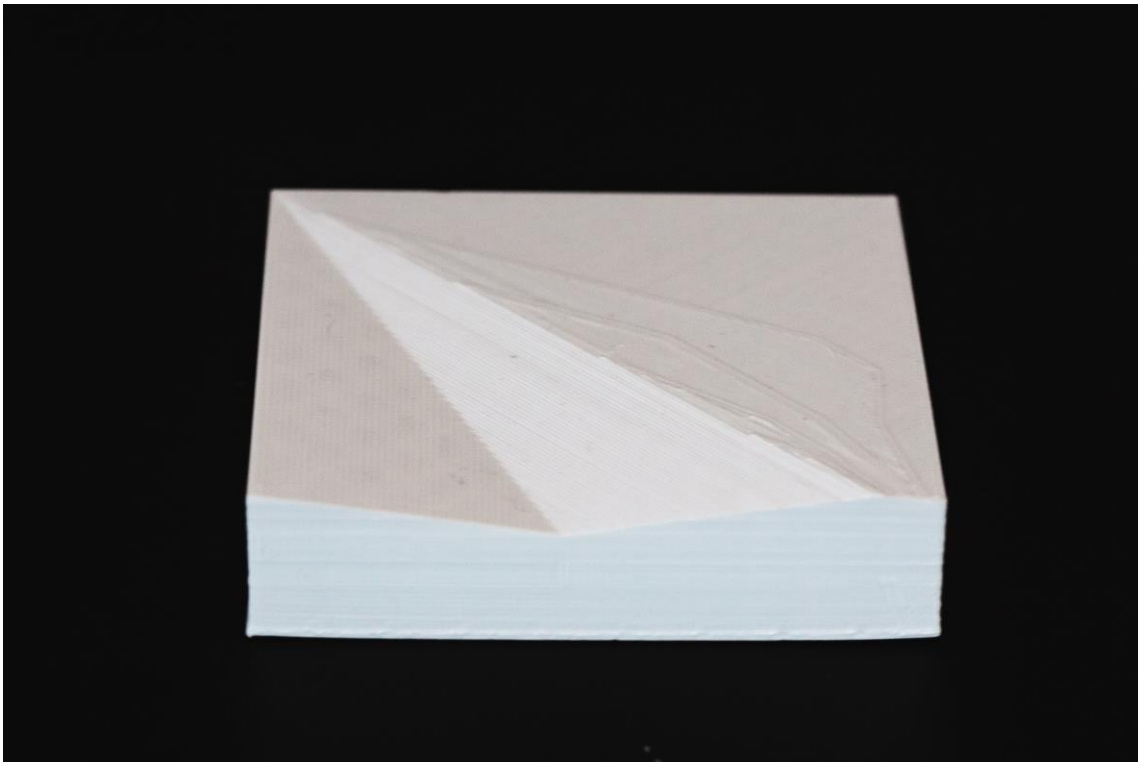


Figure 39. Standard ELH façade panel print, showing slight failure in the top surface

4.5.1 Standard 3D Printing Comparisons

The initial stage of physical experiments involved printing a series' of varying panel geometries at a small 1:10 scale, informed by the previous digital experiments, and using standardized AM methods (a flat XY-plane base, with automated print slicing) and G-Code (robotic instruction script, typically generated using Cura software). These prints were firstly used to test some of the previous findings by comparing the amount of material consumed, time used, and volume contained for some of the more efficient geometric strategies explored (displayed in figure 38). Secondly, these tests were used to identify potential shortfalls of the standard 3D printing process and subsequently establish some challenges to be explored with the following robotic experiments.

The alternative panel geometries developed saw a uniform reduction in overall material quantity used to cover the same amount of surface, however with a varying level of efficiency in material-per-volume when compared to the basic printed ELH faceted panel (figure 40). Based on the selection of single panel geometries printed, it was observed that, in most cases, shearing all panel sides into non-uniform face angles reduced material, however had a lower overall material-volume efficiency in many cases, as well as lower print time efficiency. One significant factor in these material rates was

the percentage of support material printed for each panel. The standard ELH panel print was composed of 28% infill support material due to its greater portion of flat walls, while the first altered panel in figure 36 was composed of 55% infill support material and the second was 54%. As shown in the panels compared in figure 40, maintaining some flat edge surfaces in the altered panel 2 provided significant overall benefit in print time and volumetric material efficiency over the standard panel and first altered panel, however still observed challenges in its infill material percentage due to its angled faces and thicker shell support requirements at those parts.

While no significant failures were observed using the standard 3D print process, a minor abnormality was observed on the top surface of the standard ELH panel print, (figure 39) where the surface texture was noticeably altered and inconsistent with the rest of the print. Considering this print was undertaken using standard settings for support material and shell thickness, it suggests the possible need to explore variability in material deposition and speed through the geometry in order to meet more localized need for material and precision.

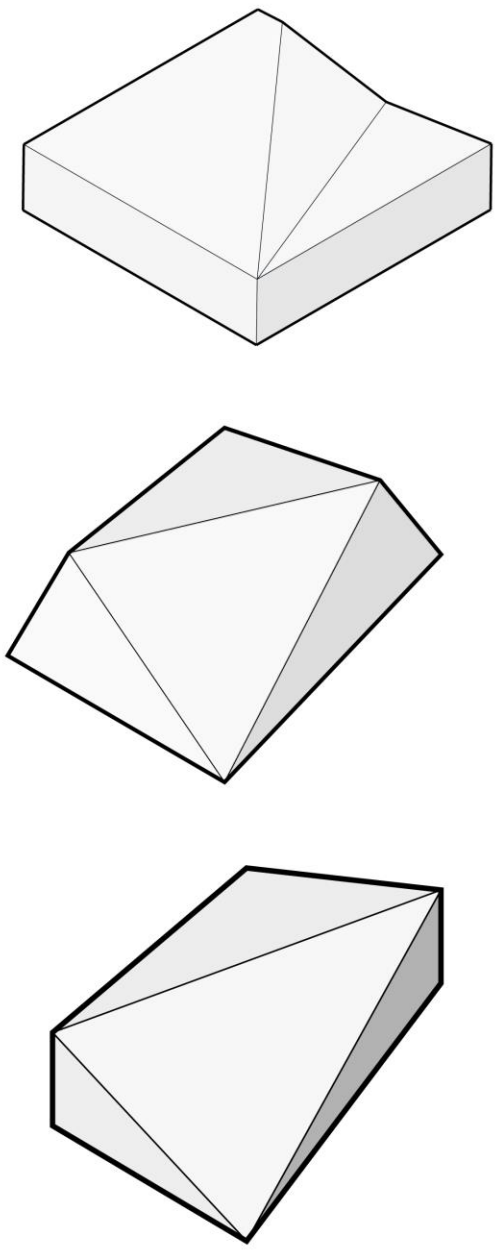


Figure 40. Compared metrics for a number of single panel geometries printed using standard AM methods

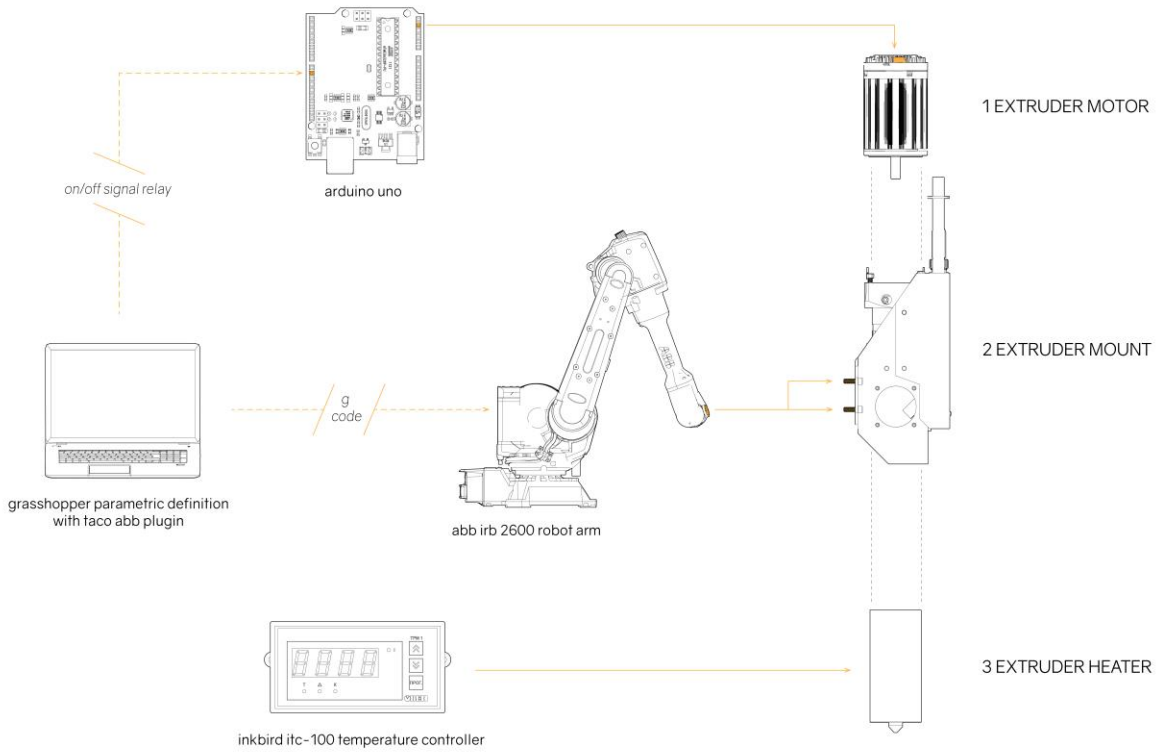


Figure 41. Control and connection overview for the robotic AM equipment setup

4.5.2 Printing Waveforms and Printing onto Geometry

The robotic printing equipment setup was developed to provide a number of variables for user control over movement and material deposition rates. Given the importance of optimizing material and time use in the printing process, these variables were important in the experimentation to avoid uniformity across the geometry and instead respond to specific localized needs. The setup used to fabricate the robotic AM experiments is showed in figure 41, in which digital code controls both robot movement and extruder motor operation, with only the extruder heater being operated on a separate control system. The initial series of robotic printing experiments were conducted to test some of these variable controls in the production of simple open geometries.

The first experiment using the robotic method looked back on the shell patterning logics explored in section 4.4.3 as potential for greater efficiency in shell printing strength and material efficiency. Considering the scale being printed and the material required, the sharp wave was selected for this experiment in order to produce the desired frequency of pattern and structural effect. This experiment only yielded one example geometry, and therefore was unable to compare the material

quantity or time of various texturing techniques, but only provide an example of the textural affect and single-line shell strength of the wave pattern to create overhangs and walls (figure 42). One interesting effect observed in this test was that the robot movement speed slowed each time it changed direction, thus depositing more material. Therefore, as demonstrated in the top right image of figure 42, the straight segments of the print have more permeability than the seams.

A significant benefit provided by the multiple axes of the robot was the ability to print onto existing geometries (as shown in Anton and Abdelmahgoub, 2018) and thereby reduce support material and provide more customizability over the base surface upon which to mount geometry. The experiments shown in figure 38 uses a cylindrical base geometry to print onto, requiring the robot to re-orient the extruder to the normal of each point in the toolpath to match the cylinder's curve. This also allowed for greater overhangs when the walls of the printed geometry matched the normal of the cylinder upon which they were printed. Furthermore, in speculating about producing future panel geometries that require non-uniform customized base wall surfaces to mount onto, this strategy provides promise in maintaining print fidelity and avoiding material or tectonic complexity.

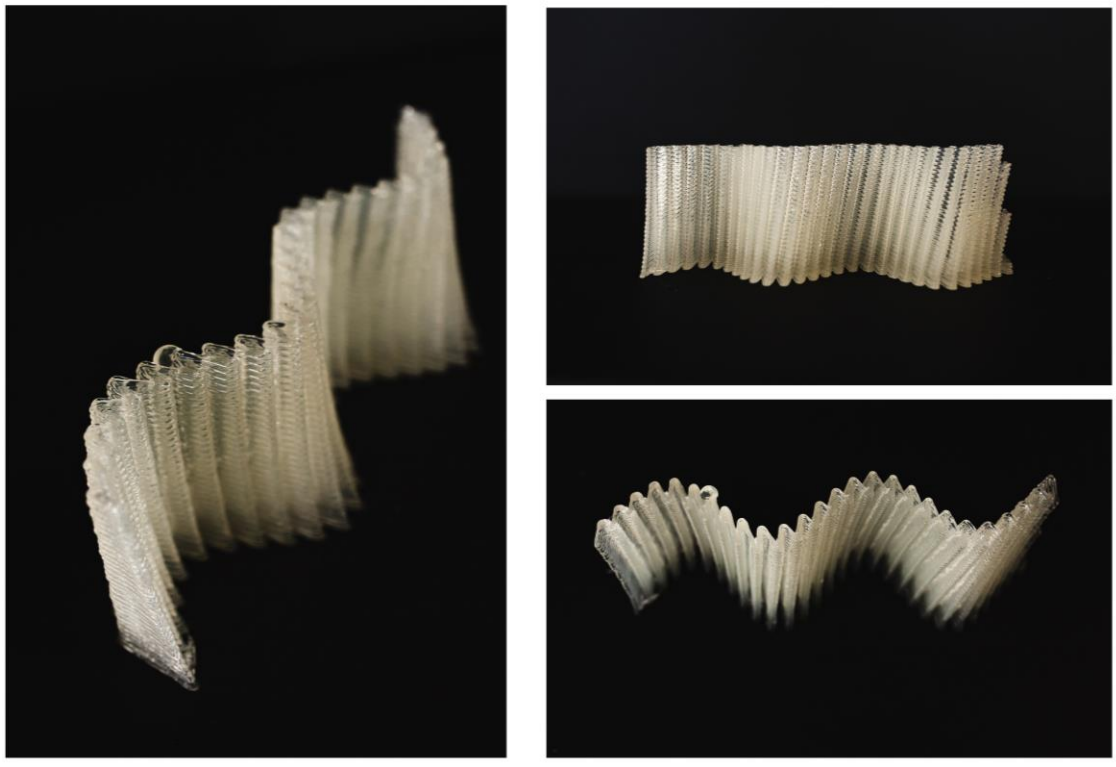


Figure 42. Wall geometry example using a waveform toolpath pattern, thus increasing thickness, strength, and overhang potential without using solid fill

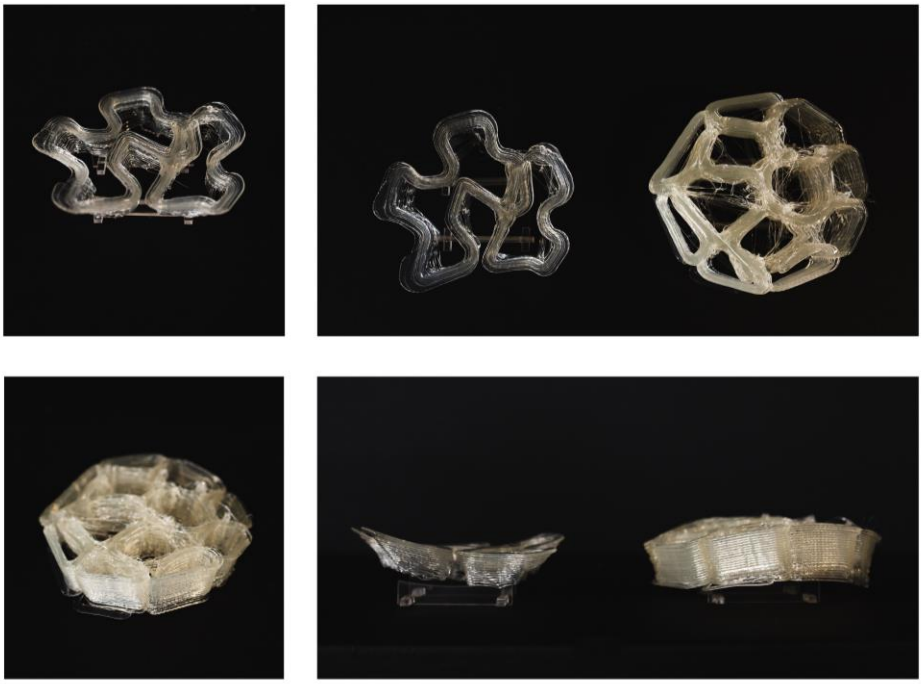


Figure 43. Robotic printing test geometries using a cylindrical base plane

However, printing onto existing forms in the more complex bottom left geometry in figure 43 produced a new challenge that required both variability over the robotic axes toolpath and the Arduino Uno motor control signal. The top left form in figure 43 used a single line printing toolpath, however when a form with multiple shapes was used, it introduced potential collisions between the extruder and the base geometry that was being printed onto, during moments where the robot moved in straight paths between different shapes and was not reorienting around the base cylinder surface. In these experiments, the toolpath was altered to add intermediary points in both the Arduino motor signal and the robot arm toolpath, where the end of every shape would signal the motor to stop while the arm lifted above the base cylinder and navigated to the next shape. As shown in figure 44, another solution to mitigate this issue could involve iteratively sorting the various shapes in the print and the seams at which printing each one starts and stops, in order to reduce the need for intermediary robot movement points between shapes. This would involve measuring the distance between a variety of potential start and end points of each shape, and calculating the shortest overall path to print every shape.

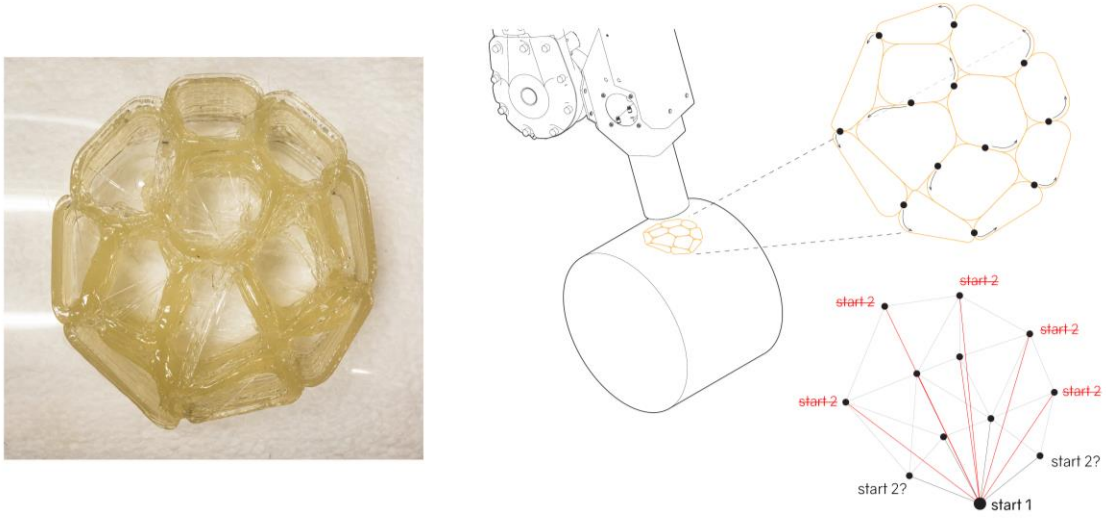


Figure 44. Challenges of sorting individual shapes and their seams to avoid collisions arise when printing onto non-flat geometry

One significant area of future exploration discovered through experiments with these variables was how to provide the designer with greater control over the material deposition rate of the extruder at certain parts of the geometry (figure 45). A second experiment attempted to print onto the cylinder formwork and alter the material deposition rate at specified points around the form that required more or less precision and material. In this process, the robotic G-Code specified different movement speeds for the robot arm as it moved back and forth across the single line form. The robot was instructed to move faster for the middle portions (as these were less precise straight lines) and slower at the end portions (figure 45). However, this only used a speed range between 20mm/second and 40mm/second and did not produce a significant visible difference in the material quality and volume throughout the form. Future attention to the Arduino Uno control code and signal might consider moving beyond the current on/off signal and explore how the extruder motor speed could have more variation in speed in order to have more control over material deposition rate. This would involve configuring multiple signals to be used within the G-Code to speed up, slow down, or set specific desired speeds at various points throughout the print. Additionally, providing digital G-Code control over the heater temperature may also provide greater control over the material deposition rate and qualtiy throughout the geometry being printed.

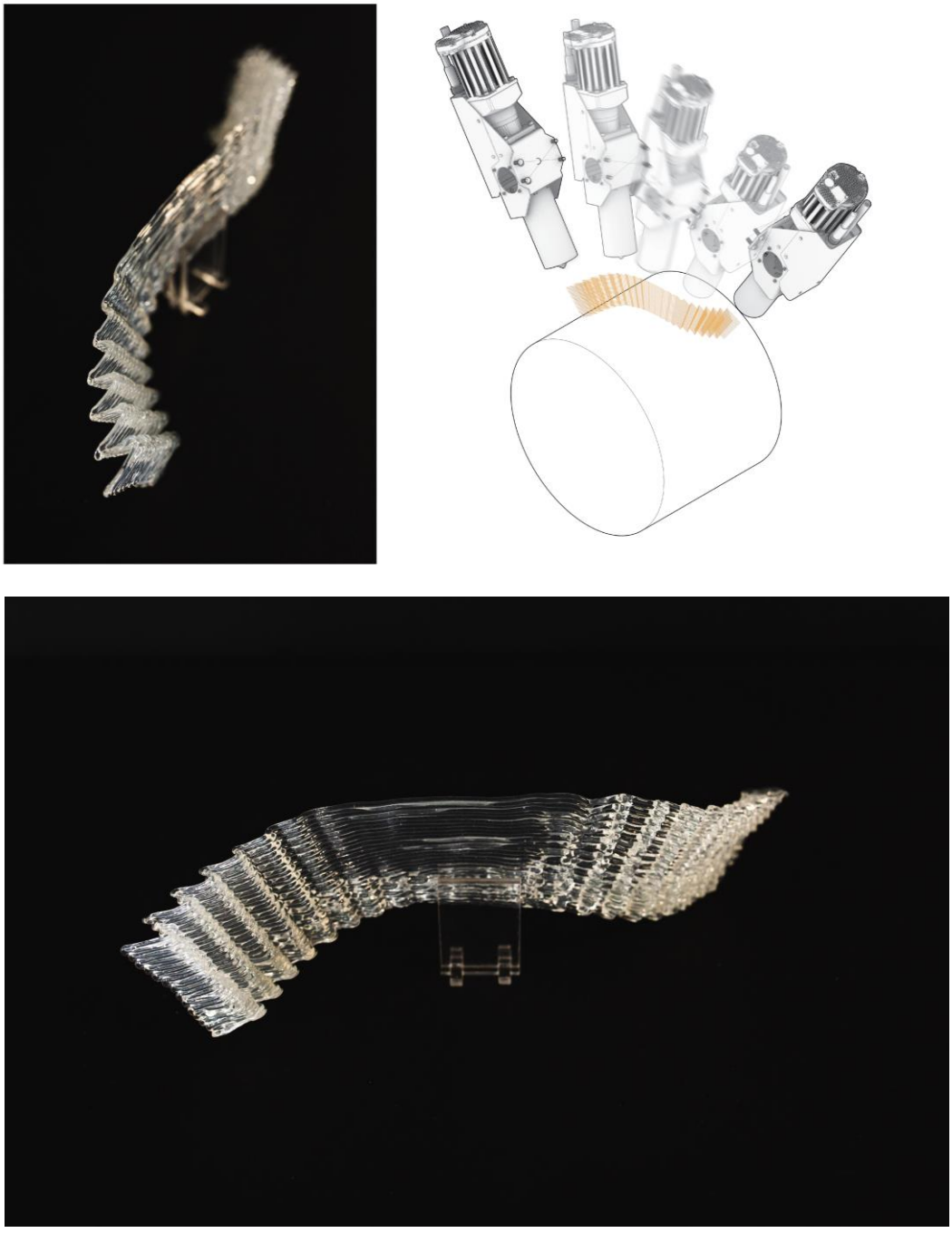


Figure 45. An experiment attempting to vary material deposition across the geometry by altering the robot's movement speed

4.5.3 Robotic Panel Printing

The final set of robotic AM experiments set out the challenge of printing one of the more angular panel iterations from the previous digital experiments without support material, in order to test the feasibility of the variable robotic orientation observed in Print Your City (The New Raw 2019), as well as variable material deposition and surface patterning explored in the previous experiments. The first step of this process was to attempt to print the angular geometry using a baseline material deposition rate (100RPM motor speed), movement speed (30mm/s), print layer increment (.8mm) and print layer angle (flat XY). This test yielded an overall failure in the form, where each layer's misalignment progressively increased by height due to the heavy overhangs and complex seams (figure 46).

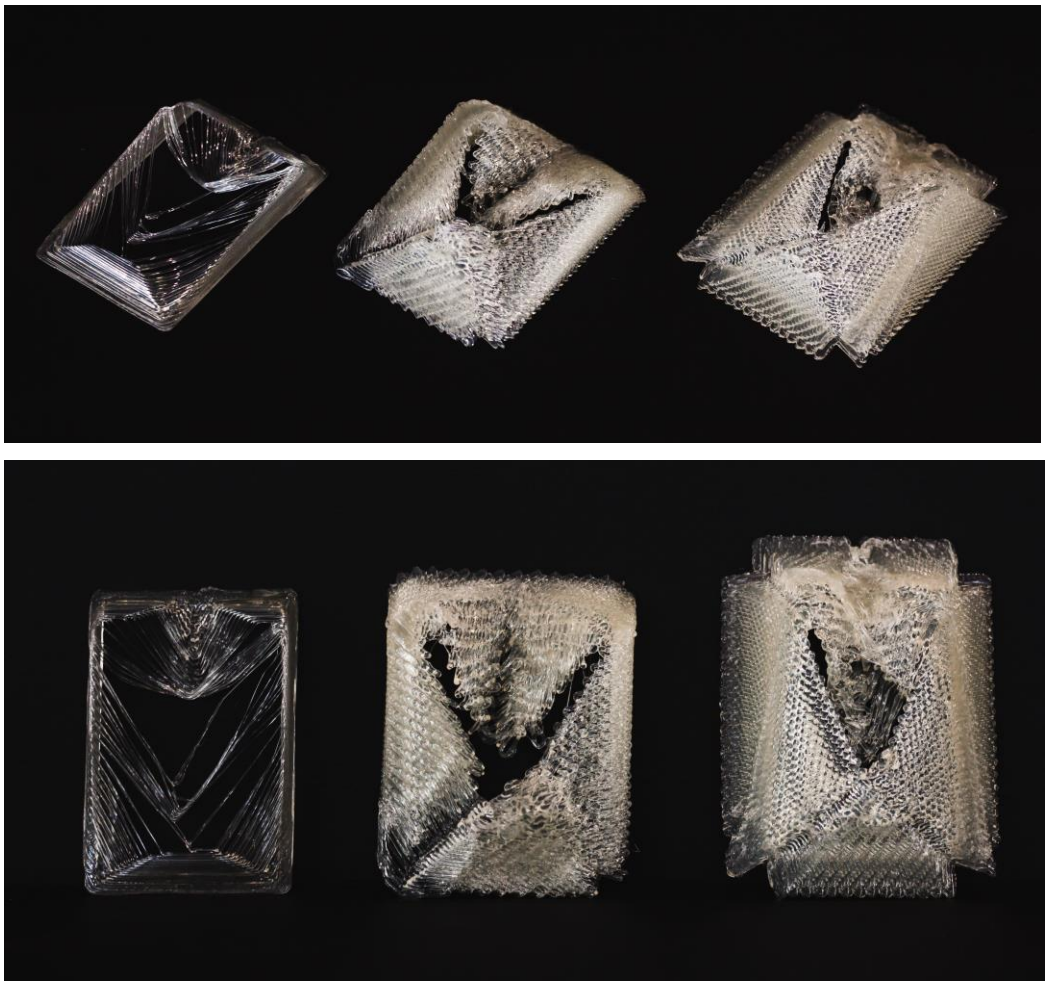


Figure 46. Print experiments 1-3 for the robotic panel experiments, using progressively higher material deposition, varying printing angles, and variable shell patterns

The second test in this series attempted to print the same form with the introduction of the waveform shell patterns, in order to increase the thickness of the walls and thereby improve bonding between layers with high overhangs. Using the waveform shell pattern and slightly higher material deposition (150RPM motor speed), this technique was slightly more successful than the original single-line print, however still failed at recreating the heavy overhangs and seams near the top of the form. In this failure, it was noted that the waveform still did not produce enough horizontal wall thickness between layers, and the vertical layer increment was still too high to allow enough gradient in the angled overhanging faces.

The third of the robotic panel printing tests was the most successful at creating the geometry. This technique used a higher-amplitude waveform shell than the second experiment, used a similar motor speed but a slower robot speed, altered the wave pattern of the form's toolpath to minimize the seam angles, and printed at variable angles relative to the geometry's faces (figure 47). These print parameters resulted in significantly more material use, with the final panel print weighting 110 grams, compared to 21 grams for the first print, 79 grams for the second, and 51 grams for the reference standard 3D printed ELH panel geometry. Therefore, while the higher material deposition much greater success at reproducing the desired form, questions may arise about the benefit comparison between reducing support material by printing more overall shell material. The technique of printing at varying angles relative to each face appeared to create better layer shapes for bonding on high angled surfaces. Furthermore, an unanticipated result of this strategy was that the robot's angle reorientation at the edges of each surface caused a momentary slowdown of its movement, and therefore created more material deposition at key seams between different faces.

Two main downsides were observed with the angled print strategy that require future experimentation with the equipment setup and toolpath variability. Firstly, using a non-flat print angle for the first layers results in lower adhesion of the geometry's base layer to the print surface. While this did not create significant failure in this instance due to the amount of material used, it may create challenges for more complex geometry, various base surface materials, and lower material deposition rates. A second significant issue created with this technique was the greater occurrence of collision between the mounted extruder, the robot joints, and the printing object. On the bottom print layers, the heating cylinder of the extruder collided with the print base when using the same angles as each geometry's face, thus requiring the print angles to be manually adjusted to be more perpendicular to the base surface. In addition, when angled faces were oriented towards the robot

and required its joints to condense, there was high risk of the mounted extruder colliding with the joints.

Some of these issues could be addressed by introducing more advanced collision detection into the toolpath itself, to identify and alter specific portions of the robot movement G Code that cause problems, such as the first series of layers, or geometry faces that are oriented towards the robot. The parametric software used in these experiments (Taco ABB plugin within the Grasshopper 3D parametric program for Rhinoceros) allows for movement simulation of the toolpath at the end of the definition to identify collisions. However, using more advanced methods, collision events in this simulation might be codified to determine their cause, and directly fed back into the toolpath definition to selectively fix these moments. Adjustments to the physical robot extruder setup could also be made to avoid collisions. Collisions with the base and heater cylinder on angled prints could be better avoided by utilizing a longer nozzle bit, while robot joint collisions might be decreased by adjusting the extruder mount geometry.

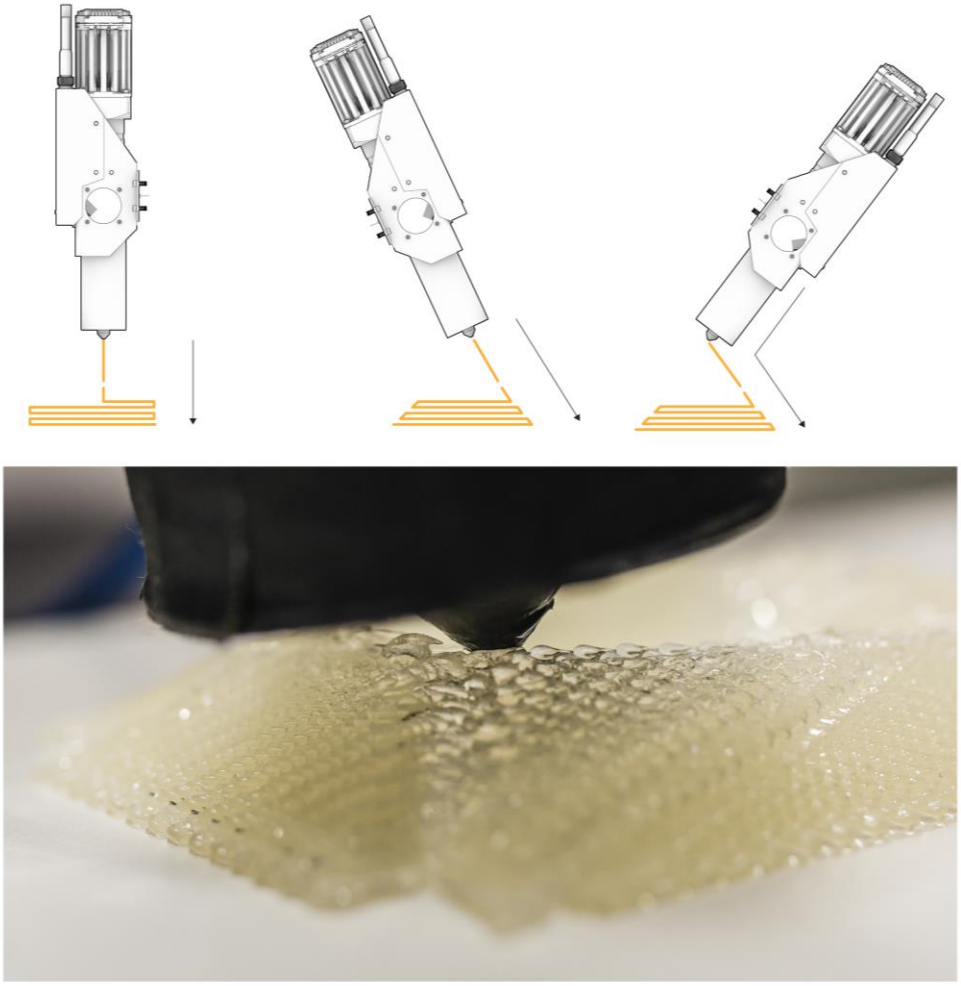


Figure 47. Varying the robot's print angle based on the surface angle in order to affect material layer bonding

4.6 Conclusion

In tandem with the advancement of large-scale additive manufacturing techniques, methods for evaluating these toolpath strategies in terms of current LCA metrics through broader scale metrics (such as transport, disposal, and more) will have to advance as well in order to provide more specific feedback and design criteria that can be fed into parametric models and robotic toolpaths. While this research looked at relatively simple material comparisons and fabrication strategies for basic printed geometry, there is an opportunity to integrate this methodology within more complex structural and topological analysis tools, as well as more advanced macro and micro-scale design techniques, in order to create multi-objective optimization and more advanced affect in various aspects of the design depending on the desired object application. Furthermore, additional physical material testing using multi-axis printing is required to better determine the relationship between material deposition efficiency, structure, and other performance, in order to determine the acceptable threshold of material reduction based on project goals.

This case study has presented a small-scale test of considerations and techniques for how new fabrication techniques for additive manufacturing could be informed by specific circular design criteria around reverse logistics, and what challenges exist for these techniques. Amongst these considerations are the translation of toolpath data and shape volumes into embodied energy in order to compare various printing strategies, the quantification of machine time and movement by toolpath lengths and rotation angles, and the amount of material used by manipulating toolpath speed and material deposition. Furthermore, these experiments also identified challenges with standard 3D printing, such as printing overhangs and thick shells with reduced support material, and varying material and precision for local requirements, and begun to experiment with the use of robotic printing methods to address them. The most successful of these early robotic tests are determined to be the cylinder form printing geometries, as they were able to achieve a relatively high fidelity and strength, while completely eliminating support material, however with an offset of higher material required in some cases.

There is a significant amount of experimental potential to continue exploring how toolpathing strategies in large-scale additive robotic manufacturing can improve circularity by both optimizing fabrication and producing affective newness. As evaluative metrics and understanding of challenges with the Circular Economy of plastic material life grows, additional opportunities will present themselves for the advancement of these design and fabrication techniques.

Chapter 5

Conclusion

The emerging shift in design materiality observed in the late-20th and early-21st century could be conceived as the move from purely physical materialism to a materialism of events distributed over time and space. Models of biological material value that revere linear physical properties of objects have begun to concede to models that instead attempt to map and address material specificity across a material's entire life in regard to broader immaterial contexts. This has yielded new types of design criteria at the material level to adhere to new circular events such as reverse logistics and supply chain management. As these criteria gain increased primacy to reduce material, energetic, and financial waste, digital design and fabrication will become increasingly critical in order to address the new levels of specificity and scale required.

This work poses several subsequent territories for design to explore. The first of these territories may be perceived as how the fabrication process creates tension in feedback loops between the geometry's function and its material optimization. For instance, it is clear from the experiments conducted that there is significant attention needed to examine the balance (and at time conflict) between performative objectives and circular objectives in material design. Some geometry (such as the more angular panel forms) was more successful in the digital simulations at increasing material efficiency, however far less successful in physical tests at being printed as a closed panel form than conventional less efficient geometry. The greater success of certain forms in the robotic print experiments could serve to either question the functional requirements of the uses they are fulfilling, or alternatively challenge the benefit of their potential material optimization with other metrics. For example, is it possible for the greater success of open geometry in the robotic print experiments to challenge the requirement of façade cladding to be series of closed forms without being a net energetic negative for the broader building's energetic footprint (for example, reducing the durability and service lives of other systems)? This question has further potential in various architectural components beyond cladding to create different tensions between their accepted functions and their potentially optimized circular forms.

Another immediate issue for future exploration is the notion of variable material form over its lifetime. As demonstrated in the Designing Out Waste (Guldager-Jensen et al, 2019) project, the potential of building material to be subtracted from by removing parts has the potential to meet changing performance criteria and better enable more efficient 1:1 material reuse with minimal added energy and money. However, the quality, condition, and nature of these materials change each time the materials are are re-processed and reused. It will be important to question how the physical form and fabrication of material may change to acknowledge and enhance multiple lifespans, such as

becoming geometrically simpler and less-performative as the material becomes more degraded with repeated processing and reuse (particularly in thermoplastics, as they can be formed and re-formed). Based off Touw's (2006) conclusion that material reuse should not be contingent on maintaining a specific physical form, we might use Deleuze's concept of the virtual to also question how material may be designed for and managed at the molecular level in its reuse (DeLanda, 2015).

This notion suggests a second major scalar territory for future investigation in how digital design tools will shift to respond to the event scale of the total material life. A significant complementary concept to Meillassoux's contingency theory is Deleuze's notion of the virtual (DeLanda, 2015), which implicates the potential of contemporary digital tools in this problem. The virtual describes the inherent capacity of physical materials to perform various functions and change to various different states. As described by Deleuze, all virtual properties of material are "strictly a part of the real object," (DeLanda, 2015, p. 18), however cannot all be actualized at once, or necessarily ever. Contemporary digital tools such as BIM are therefore, in essence, models which attempt to capture some virtual properties of a building (which materials may be used, what its energetic performance may be, and more) in order to inform how the building is actualized. However, as demonstrated through this paper, the building is also actualized through broader-scale contingent factors at the individual material level such as cultural value models, therefore we must question how digital tools may advance to virtualize these broader aspects. For instance, tools such as the material passport discussed in this paper are capable of tracking matter at the level of building materials, however may require radical technical evolution in order to track matter at its most base levels and enable it to be deliberately re-designed at varying points in its lifespan while monitoring its condition, value, age, and more. Furthermore, parametric models may also advance in order to better parameterize time and space-based data over broader scales and in much more significant quantities (for example, tracking market data for material value and utilizing it as a dynamic parameter to inform material use or saving in design at one or multiple points in time).

The question of how economics may shift to respond to broader material events is another tangential path to explore as a result of the concepts in this work. Many of the concepts discussed, such as reverse logistics, provide an introductory point into understanding how virtualization with tools and design models might advance in scope through the shift of economic models. For instance, if building removal becomes an integral part of an initial building's capital budget, then virtual models might attempt to simulate and optimize reverse logistical costs for materials at the end of a building's life. These models might inform how to minimize building removal costs through up-front design decisions, or even generate return through the value of materials that can be

recovered and reused. As stated by Beamon, the potential value of recovered building material is based largely off the quantity, proximity, and capability of processing facilities (1999, p. 338). Therefore, collaboration between designers and local waste management at the initial stage of a building's design might be able to yield specific material recovery cost and/or return figures that can link to decisions in a virtual model. Using such models might also allow designers to virtualize the value of a building against the value of its respective materials at any given time based off market factors for space, building material, and/or raw material.

At a physical level, the experiments produced in chapter 4 of this work demonstrated some added benefit of customized geometry and robotic processes over standardization in their ability to meet contingent circular metrics, however also posed many more challenges due to their greatly increased spatial complexity. The assumption that digital fabrication techniques such as additive manufacturing can produce higher customizability without significant additional labour was challenged by the various issues discovered and addressed in the robotic printing process. In particular, the collisions introduced by the multi-angle printing required a significant amount of troubleshooting and customization that was unique each individual shape and placement. As discussed in section 4.5.3, avoiding the extra labour required in this technique may require more sophisticated simulation and automated feedback systems within the digital tools being used. These systems would require the ability to serialize errors caused by movement and the environment in order to automatically determine the toolpath adjustment required to correct them.

In closing, Meillassoux (2008) makes the argument that nothing is necessary, meaning that no single physical material property can linearly create absolute value or use without meeting contingent conditions and balancing with other metrics. The experiments in this work make a strong argument for the merits of customized material and processes, however only consider a very limited scope of metrics and contingencies for this material. The future of the design approaches presented here must ultimately aim to better translate the concepts of the possibility space and the singularity (Meillassoux, 2008) into more integrated and tangible feedback systems that negotiate requirements of circular and supply chain constraints (material availability, time availability, volumetric goals or area-based goals, cultural value models, and functional performative requirements for each individual material case.

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