BUILDING EQUITY:

LEVERAGING TECHNOLOGY FOR AFFORDABLE HOUSING IN SEATTLE, WASHINGTON

by
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Abstract

The United States is currently experiencing the most significant housing crisis in its history. With over half of households spending more than 50% of their income on housing, households are unable to afford housing that is truly affordable to them. These conditions are intensified further in households of color and low income. In cities that have experienced rapid economic and population growth, like the city of Seattle, Washington, increased property values and low vacancy rates have highlighted the need for affordable housing development.

Through this research, I am to answer the following primary question, “How are existing technologies currently advancing the design, construction, and scalability of affordable housing?” In approaching this work, I first gathered geographic context to distill the unique characteristics of housing stock, growth, and capacity in Seattle. Then, I researched and inventoried 14 major construction technologies to then analyze and develop a strategic recommendation for phasing and technology implementation for affordable housing development in Seattle.

Within the analysis, I confirmed that construction costs did encompass a majority (54%) of the development cost of completing an affordable housing unit. I found that three primary trade areas contributed to 62% of the total construction costs: Interior Finishes, Framing, and Rough-ins. In order to create efficiencies within these scopes on site, there are a variety of ways that construction technologies can be implemented and prioritized. Engaging innovations early on in a development process, especially for resource constrained affordable housing development projects, can be instrumental in extending funding further. There is a significant opportunity to reduce overall development costs for affordable housing to pave the way for building more stock and ultimately meeting the overwhelming demand that exists both in Seattle and at a national level.

Keywords:

Affordable Housing, Construction, Technology, Innovation, Digital Transformation, Housing Insecurity, City of Seattle, Application, Modernization

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Section 1: Introduction

The US Housing Crisis

"Skyrocketing home prices and rents create housing crisis" (Yang, 2022), "The American Dream needs an extensive renovation" (Bloomberg, 2022), and "The U.S. needs more housing than almost anyone can imagine" (Lowrey, 2022) are just a few of major news headlines being published in 2022. *The U.S Housing Crisis* is a phrase that has become commonplace over the last 5 years to describe the storm of disruptive conditions such as rising rents, lack of housing supply, and restricted access to loans that has created barriers to homeownership. While these conditions affect a majority of residents in the United States, they are particularly debilitating for low income communities and exacerbate the already-prevalent factors that prevent these marginalized communities from securing affordable housing.

The U.S. Department of Housing and Urban Development defines *affordable housing* as "housing on which the occupant is paying no more than 30% of gross income for housing costs, inclusive of utilities" (U.S. Department of Housing and Urban Development, 2011). Households spending more than 50% of their income on housing costs are considered severely cost burdened. According to a March 2022 Statista study, the share of gross rent in household income in the United States ranges dramatically across households. As shown in Figure 1, over half of U.S. households spend more than 30% of their income toward housing, with a shocking 40% of U.S. households spending 35% or more of their income on rent (Statista Research Department, 2022). This effectively means that most residents in the United States are unable to find housing that is affordable for them.

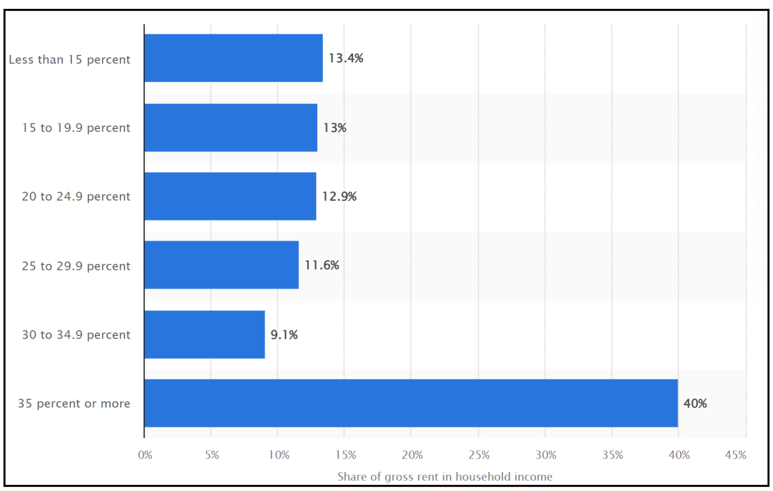


Figure 1: Gross Rent as a percent of household income in the US (Source: Statista, 2022)

Furthermore, this statistic doesn't take into account the disparities across gender, race, ethnicity, socioeconomic status and geographic location that further intensify the proportion of income spent to obtain secure housing. Within lower income communities, spending over 30% of their earnings on housing means that families are often left with insufficient financial resources to cover basic necessities after paying for housing. Some additional key definitions are noted below in *Figure 2* and a visualization of the affordability spectrum is shown in *Figure 3*.

Key Definitions

Area Median Income (AMI): The median family income in the metropolitan or nonmetropolitan area
Extremely Low-Income (ELI): Households with incomes at or below the federal poverty guideline or 30% of AMI, whichever is higher
Very Low-Income (VLI): Households with incomes between ELI and 50% of AMI
Low-Income (LI): Households with incomes between 51% and 80% of AMI
Middle-Income (MI): Households with incomes between 81% and 100% of AMI
Above Median Income: Households with incomes above 100% of AMI
Cost Burden: Spending more than 30% of household income on housing costs
Severe Cost Burden: Spending more than 50% of household income on housing costs
Affordable: Housing units with rent and utilities that do not exceed 30% of a given income threshold
Affordable and Available: Rental units that are both affordable either vacant or not occupied by higher-income households

Figure 2: Key Definitions related to Housing and Affordability (Source: National Low Income Housing Coalition)

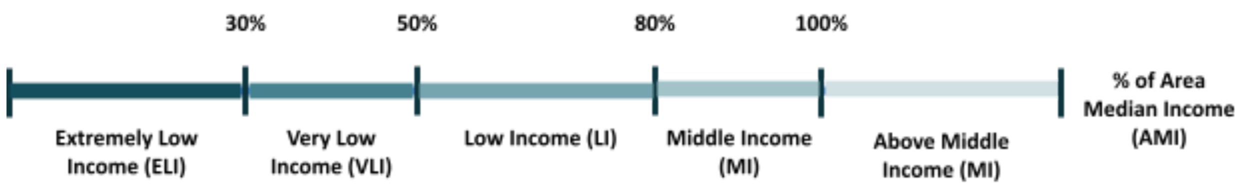


Figure 3: Spectrum of Income categories as a percentage of Area Median Income

The National Low Income Housing Coalition spearheads the development of *The Gap*, an annual report documenting the shortage of affordable and available housing to low and extremely-low income families. While housing is more available to those who are at 100% of AMI or higher, renters with very low income and extremely low income levels are lacking a supply of housing options affordable to them. For every 100 extremely low income renter households, there are only 33 affordable and available rental homes (National Low Income Housing Coalition, 2023).

Of the nation’s 11 million extremely low-income (ELI) households, it is estimated that only 7 million units are affordable using the definition of affordable housing as not exceeding 30% of income spent on housing. This results in a large deficit of housing that is determined affordable. Furthermore, of the 7 million units affordable to ELI households, only 3.7 million units are actually accessible due to vacancy or rents set at an ELI-affordable range. The remaining 3.3 million of the 7 million original units are currently occupied by households who are considered low income, very low income, and middle income. In other words, ELI households are both experiencing a deficit in affordable housing and in available housing which forces them to rent homes they are unable to afford. This situation leaves ELI households with no choice but to experience severe housing cost-burden.

According to the National Low Income Housing Coalition's 2022 *Out of Reach* report, "in no state, metropolitan area, or county in the U.S. can a worker earning the federal or prevailing state minimum wage afford a modest two-bedroom rental home at fair market rent by working a standard 40-hour work week" (National Low Income Housing Coalition, 2022). In California, New York, Massachusetts, New Jersey, Washington DC, and Washington State, workers need a minimum wage of over $30/hour to afford fair market rent for a two-bedroom rental home without paying more than 30% of their income. Table 1 below compares wages needed in the United States overall to those needed in Washington State.

Category	Data Metric	United States	Washington
FY22 Housing Wage	Hourly Wage Necessary to Afford 2B FMR	$25.82	$31.33
Housing Costs	2BR FMR	$1,342	$1,629
	Annual income needed to afford 2 BR FMR	$53,669	$65,161
	Full-time jobs at minimum wage needed to afford 2 BR FMR	2.4	2.2
Area Median Income (AMI)	Annual AMI (household)	$92,091	$108,911
	Monthly rent affordable at AMI	$2,302	$2,723
	30% of AMI	$27,627	$32,673
	Monthly rent affordable at 30% of AMI	$691	$817
Renter Households	Renter Households	43,928,837	1,067,763
	% of total households	36%	37%
	Estimated hourly mean renter wage	$21.99	$27.55
	Rent affordable at mean renter wage	$1,144	$1,433
	Full-time jobs at mean renter wage needed to afford 2 BR FMR	1.2	1.1

Table 1: Wages Needed for housing in the US and WA (Source: National Low Income Housing Coalition, 2023)

There is a disproportionate burden placed on Black, Latino, and Women since renters of colors historically have earned less than white renters as a result of deep rooted discrimination and restricted access to opportunity. Furthermore, workers of color are more likely than white workers to be employed in sectors with lower median wages, while white workers are more typically employed in higher-paying managerial positions. In 2019, the median black worker earned 24.4% less per hour than the typical white worker and "less than half of the observed black-white difference in average hourly wages is explained by differences in education, experience, or religion [which are] the main factors presumed to determine pay" (Wilson & Darity Jr., 2022). With black workers unable to 1) seek employment and 2) be fairly compensated compared to their white peers, they are more likely to struggle to afford housing in the fair market. As shown in *Figure 4* below, households of color are more likely than white households to be renters and have extremely low incomes (NLIHC, 2023).

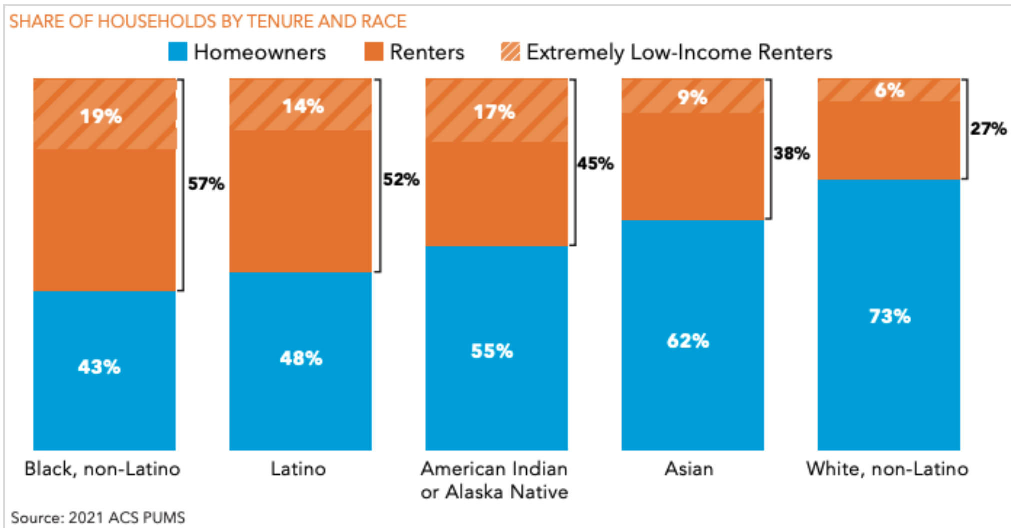


Figure 4: Share of ELI households by Race (Source: National Low Income Housing Coalition, 2023)

The COVID-19 pandemic has only exacerbated housing insecurity for the most vulnerable populations. With the most significant unemployment rates in recent history, low income households that experienced job insecurity were forced to spend an even greater percentage of any income the household received towards housing. Nearly 11 million renter and homeowner households were overdue on their housing payments in December 2020, leaving households exposed to heightened risk of losing their homes to foreclosure and eviction (Wong, 2021). Research has shown that eviction and housing displacement not only expose households to COVID-19 infection but also leaves households without financial access to healthcare and greater risk of mortality amongst the lowest income households (Benfer et al., 2021). This greater risk of vulnerability only underscores the importance of the United States to invest in increasing availability of affordable housing across the income population. This need is particularly important in parts of the country where market conditions make housing unaffordable across all income levels.

The Affordable City

There are a plethora of explanations for the dire state of the lack of affordable housing in the United States, but I have found Phillips' Three S's framework helpful in organizing the intervention areas we can pursue to develop solutions. In his book *The Affordable City,* Phillips argues that both the technical and political solution to the American housing crisis can be found by "coequally prioritizing the Three S's: Supply, Stability, and Subsidy" (Phillips, 2020). Phillips defines the Three S's as following:

Supply	Having enough housing for everyone
Stability	Recognizing the dignity of housing - and the need for supporting those in housing to maintain security in it
Subsidy	Ensuring everyone enjoys the benefits that come with abundant housing and stable communities

Table 2: Definitions of the Three S's by Shane Phillips in *The Affordable City*

Philips goes on to explain the importance of these categories in contributing to the current state of our national housing crisis, as well as acknowledges that "the Three S's are sometimes in tension" (Phillips, 2020). In these scenarios, he argues that planners, policy makers, and advocates of affordable housing development should align on pro-housing policies where the number of beneficiaries outweigh the number of people who are harmed. In other words, policy will rarely be able to equally address issues of supply, stability, and subsidy, but striving for action that creates the most overall impact across the spectrum of issues will lead us more quickly towards significant progress.

In order to meaningfully investigate, challenge, and develop solutions that move the overall needle towards affordability, I have chosen to focus this thesis on the issue of supply (or lack thereof) and its role in exacerbating the U.S. housing crisis. When there is a lack of housing availability to begin with, the remaining housing options become unaffordable and therefore, unattainable. Phillips urges that "we must make it easier to build housing, and do so in a thoughtful and careful way, to have any hope of creating more affordable and accessible cities " (Phillips, 2020). He goes on to structure the supply argument into two primary components: the rate of new development and the vacancy rate.

Phillips argues that the fundamental theory of supply and demand applies in many cases to explaining affordability. He posits that "if a city is able to match the supply of new housing to growing demand, the cost of building new housing shouldn't rise any faster than the overall rate of inflation" (Phillips, 2020). There are a plethora of reasons that impact the supply of housing: from rising labor costs, lack of material availability for construction, zoning restrictions, and unprecedented demand from higher-earning households. Secondly, if cities are experiencing low vacancy rates compared to national averages, renters are seeking unavailable housing which increases market power to landlords.

There are a number of policies that Phillips suggests tackle the issue of increasing housing supply. 8 of these policies are listed and summarized below:

1. <u>Increased Zoning Capacity:</u> Also referred to as *Upzoning*, this land use regulation describes the process of modifying zoning designations of parcels to accommodate for greater density. This ultimately paves the way for legally building more housing. Many cities looking to increase affordable housing will utilize this strategy to increase housing stock to meet projected population growth.

2. Geographic Upzoning: This strategy is mindful of the potential gentrification and displacement that singular communities can face when upzoning happens in their neighborhoods. Geographic upzoning targets a multitude of areas so that development occurs in smaller quantities all across a city and the impact doesn't burden any particular community.

3. Targeted Upzoning: Similar to geographic upzoning, this zoning strategy increases residential densities in high-opportunity areas where relatively affluent households live and reduces gentrification pressure on lower-income neighborhoods.

4. Rightsized Upzoning: This policy takes into consideration the unique geographic conditions of an area in order to determine the density that would best suit those neighborhoods. It is a form of incremental development that takes into account historical reactions to zoning and growth projections to tailor land use zoning to that area.

5. Mixed-Use Zoning: This zoning strategy allows for the increase of housing supply by permitting housing development in commercial zones. This zoning type can take on many forms of development such as housing plus office, office plus hotel, etc. Many cities in the United States are moving towards banning purely residential zoning in favor of mixed-use zoning.

6. Develop Barriers to Home Sharing: When property owners are incentivized to home share (ex. Airbnb) through high nightly rates, they are less likely to rent out their properties as long term rentals. This effectively reduces the housing stock available to those looking to rent housing for their primary residence. Some cities are regulating short-term rentals to combat home sharing.

7. Eliminate Density Limits: Through this policy, developers are held to standards such as maximum building heights and maximum floor area ratio rather than density limits to create more homes. This strategy often leads to greater diversification of properties and leads to accommodation of accessory dwelling units or other forms of housing.

8. Eliminate Parking Minimums: When parking is required to be built in conjunction with new housing and commercial developments, it is found that often more parking is built than needed. This results in vacant lots that take up prime real estate space that can be used for building more housing. Through elimination of parking minimums, cities can encourage residents to take other forms of transportation.

The Affordable City outlines a variety of other policies that can be utilized to increase the supply of housing in cities. These recommendations largely call for zoning reform, diversifying housing typologies, and finding ways to speed up the development process in efforts to build more. While local efforts to adjust current land use and zoning practices is extremely necessary, private-market development in conjunction with funding directed towards state and local government housing programs can add much needed housing inventory at a faster pace. This thesis will explore these particular conditions and offer possible innovative interventions that could reduce current constraints.

Construction Technology

Despite contributing over 13 percent of the global GDP (and making it the biggest industry in the world), Construction has seen a "meager productivity growth of 1 percent annually for the past two decades" (João Ribeirinho, Mischke, Strube, Sjödin, Luis Blanco, et al., 2020). The field of construction has undoubtedly lagged in embracing digital technology solutions at the rate of other industries, but the last fifteen years have brought much-needed innovation to this antiquated industry. As defined by the Construction Institute, construction technology refers to the "collection of innovative tools, machinery, modifications, software, etc. used during the construction phase of a project that enables advancement in field construction methods" ("CII - Construction Technology," n.d.).

The sheer magnitude of the construction industry on the global economy has brought in major interest and venture capital investment into the construction technology space. By the late 2010s, technology was being leveraged to deliver singular pointed solutions which "addressed basic needs such as digitizing paper-based information and improving design capabilities" (Bartlett et al., 2020). Point based and single-issue technological solutions have since evolved into incorporating technology into many facets of the construction process from digital collaboration, back office work, and onto the job site.

From 2010 to the start of 2020, global construction output grew to a staggering $10.7 trillion dollar industry and is projected to hit $15.2 trillion by the end of the decade in 2030 (Robinson, Leonard, & Whittington, 2021). Furthermore, the COVID-19 Pandemic accelerated growth significantly as the industry was pressed to adopt digital collaboration tools and practices as well as heighten safety standards for essential workers. Oxford Economics anticipates that global growth in construction will exceed both manufacturing and service sector trajectories by 2025. Finally, in line with current trends of rising population levels, the demand for more housing units continues to sustain.

Innovations in construction technology are projected to help meet this demand through increased efficiencies in the construction process. As documented in Section 6 of this thesis, a significant portion of the costs associated with bringing affordable housing units to market is the construction cost associated with the development project. This immense need for reducing construction costs for housing development combined with the circumstances of the COVID-19 pandemic has exponentially increased the investment that the industry is placing in developing construction technology. The industry landscape, current market trends, and overview of prominent technologies across the maturity spectrum are discussed in further detail in Section 5.

Why Seattle

Mostly known for its geographic location at the upper northwest corner of the United States and its chronically rainy climate, the City of Seattle feels relatively tucked away from the rest of the country. However, the city has been vitally important for the national economy and is one of the fastest growing cities in the United States. Driven by technology giants such as Microsoft and Amazon, Seattle's GDP has seen a 110% increase over the past decade, elevating the city to the position of the 9th largest economy in the U.S. with a GDP of $480B (Koop, 2023). Today, Seattle is currently the third fastest growing city by measure of year-over-year GDP growth at 3.5% (The Kenan Institute, 2022). Beyond software and biotechnology industry booms, this growth can also be attributable to Seattle cementing its place as a leader in climate technology development and a scientific hub for Clean Tech.

With all this economic growth, Seattle has experienced rapid growth and development over the past 30 years, from a population of approximately 493,000 in 1980 to over 737,000 today. Rapid growth has resulted in extreme changes in affordability in the city. According to the Council for Community and Economic Research's (C2ER) Cost of Living Index, the costs for goods and services in Seattle range from 9%-40% higher than the average rates in the United States overall, making Seattle the 6th most expensive U.S. city to live in (Balk, 2021). Since 2014, the average Seattle home value has increased from $455,000 to nearly $835,000 (Zillow, 2023). Seattle's impressive population and economic growth combined with its unique geographic location make it an attractive choice to situate this thesis work. With a City government committed to combating displacement and a market economy focused on innovation and technology, the City of Seattle will provide a useful background to apply the thesis focus.

Section 2: Thesis Framing

Thesis Framing

Recognizing that (1) there is a dire need for creating more affordable housing and (2) construction technology continues to evolve at a rapid pace, I aim to explore the research question:

How are existing technologies currently advancing the design, construction, and scalability of affordability?
What are the promising areas for expansion/development?

Furthermore, in order to account for variances in local legislation, accessibility, and relative affordability, I will be investigating this question within the geographic constraints of the Seattle, Washington metropolitan area. The City of Seattle was chosen primarily for personal reasons - as a future resident of Seattle, I felt this thesis provided a unique opportunity to understand real estate and housing conditions prior to the cross country move. Also, as a rapidly growing city with conditions similar to San Francisco in terms of geography and economy, I was curious to investigate how trends on housing affordability compared across the two cities.

Study Methodology

There are 4 major goals that I hope to accomplish through the preparation and presentation of this thesis:

1. Develop a *strong foundation of geographic context* to understand Seattle, its unique affordability challenges, and opportunities to incorporate construction technology solutions into policy and practice.
2. Inventory the *current landscape of innovations* in the construction technology sector, with specific emphasis on solutions that advance building construction and help increase accessibility of services and support to communities.
3. Recommend potential investment areas within the construction technology industry based on perceived impact, costs, and applicability to the Seattle metropolitan area.
4. Document industry trends to *predict key innovation areas* in the near-term future.

I will accomplish these objectives through a combination of literature analyses, conducting interviews with industry professionals, developing an evaluation framework of emerging construction technologies, and applying this framework to maximize the impact of generating more supply of affordable housing in Seattle.

Section 3: Geographic Context

Early History

The history of Seattle is rooted in indigenous culture and tradition as it was built on the territory of the Coast Salish peoples. European settlers established a claim on the Seattle area in 1851 when they arrived at Alki point, affecting the Duwamish and Suquamish Tribes who were long-time residents and stewards of the area. The village was renamed soon after to Seattle after the Duwamish leader named Sealth. The primary economic activity in the region was generated by logging and the lumber industry and was later supported by trade through the transcontinental railroad, the growth of the fishing industry, shipbuilding, and shipping. Post World World II growth is largely attributable to the success of the Boeing company, which established Seattle as one of the epicenters of aircraft manufacturing. The 1962 Seattle World's fair is thought to have spurred a "renaissance in the Pacific Northwest that saw it emerge as a major tourist destination and one of the country's most livable cities" (Robinson & Hatfield, 2023). During this time, the City became a home for its arts and cultural institutions, live theaters, and sports arenas.

Physical Geography

The City of Seattle is geographically situated on a narrow strip of land between the Puget Sound - a deep 100 mile long inlet of the northern pacific ocean - and Lake Washington. It is located at latitude 47.39'N and longitude 122.17'W, approximately 90 air miles east of the Pacific coastline and 113 miles south of the U.S. Canadian border. Seattle is surrounded by great natural landscapes on its sides, from the forested mountain ranges of the Olympic peninsula on the west to the Cascade range on the east. The chief harbor of Seattle is Elliot Bay, part of the Puget Sound. Its location in the Pacific Ring of Fire leaves the City vulnerable to earthquake activity, which it has experienced on several occasions in 1949, 1965, and 2001. The physical area of Seattle is 142.5 square miles, of which 83.9 square miles is land and 58.7 square miles of water (Gregory Lewis McNamee, 2019). Seattle is best known for its rainy climate, with an average rainfall of at least 0.01 inches of precipitation on 150 or more days.

Seattle Today

The city of Seattle today is a diverse and bustling metropolis. As noted in *Table 3* below, Seattle's population of 737,015 makes it the 18th largest city in the United States and the largest in the Pacific Northwest. The residents of Seattle are both productive and educated, reflected in an overall employment rate of 69.2% and educational attainment of a bachelor's degree or higher of 68.3%. Comparatively, the United States national employment rate is 58.6% and educational attainment is 35% (S1501). Upon first glance, it appears that there is a surplus of housing availability for the 351,650 households present in Seattle. However, as described in the introduction previously, these housing units are not attainable for income-impacted residents and fail to support those in need of affordable housing.

Seattle At-a-Glance		
Metric	*Value*	*Source*
Population	737,015	2020 Decennial Census
Employment Rate	69.2%	2021 ACS 1-Year Estimates
Median Household Income	$110,781	2021 ACS 1-Year Estimates
Bachelor’s Degree or Higher	68.3%	2021 ACS 1-Year Estimates
Total Housing Units	368,308	2020 Decennial Census
Total Households	351,650	2021 ACS 1-Year Estimates
Without Health Care Coverage	4.0%	2021 ACS 1-Year Estimates
Hispanic or Latino	60,563	2020 Decennial Census

Table 3: Seattle-Area Metrics derived from Census Data Collection

Seattle is unsurprisingly the most expensive city in the State of Washington, and as such, has a median household income that far exceeds the State and Country at large. While the poverty rate is below that of the United States, it is higher than that of the State of Washington.

	Seattle	Washington	USA
Median Household Income	$110,781	$84,247	$69,717
Poverty Rate (% below poverty level)	11%	9.9%	12.8%

Table 4: Income and Poverty on a National, State, and Local level

When comparing the three major cities in the North West, Seattle compares closely to the poverty rate of Portland and San Francisco. The Median Household Income in Seattle is far greater than that of Portland and just shy of neighboring tech-opolis and famously unaffordable San Francisco.

	Seattle	Portland	San Francisco
Median Household Income	$110,781	$79,057	$121,826
Poverty Rate (% below poverty level)	11%	12%	11.3%

Table 5: Income and Poverty in Three West Coast Cities

The Economic Policy Institute's (EPI) Family Budget Calculator measures the income needed for a family to obtain a modest standard of living. According to this resource, it is calculated that the cost of living for a two-parent, two child family in King County, WA is $109,434 per year/$9,119 per month prior to taxes. Of this monthly cost of living, it is estimated that housing expenses will cost nearly $1,952 per month which makes Seattle and Bellevue some of the most expensive areas in the country to live in (Economic Policy Institute, 2020).

Housing in Seattle

As shown in *Table 6*, housing in Seattle is expensive with a median gross rent nearly 20% higher than that in Washington and 50% higher than in the United States overall. Homeownership rates drop significantly in the city when compared to the State and the Country, aligning with the notion that rising property values make homeownership more difficult to obtain. In fact, compared to the national percentage of owner-occupied housing units at 65.4%, residents in the Seattle area are mostly renters as 54% of all housing units in the city are occupied through means of renting.

Over the last decade, the median gross rent for the City of Seattle has increased at a much higher rate than that of the State of Washington and the United States at large. Rent in Seattle has jumped by nearly 43%, while the state increase was 37% and the United States experienced a 27% increase. Homeownership rates have been relatively constant over the last ten years and vacancy rates have actually decreased overall, prompted by an influx of residents to the State for economic opportunity.

	Seattle		Washington		United States	
	2021	2011	2021	2011	2021	2011
Median Gross Rent	$1,787	$1,024	$1,484	$930	$1,191	$871
Homeownership Rate	46%	45.8%	64%	62.8%	65.4%	64.6%
Housing Units	368,308	305,397	3,202,241	2,907,605	140,298,736	132,316,248
Housing Occupancy	345,627	282,492	2,974,692	2,632,621	126,817,580	114,991,725
Vacancy Rate	6.2%	7.5%	7.1%	9.5%	9.6%	13.1%

Table 6: Housing Characteristics on a National, State, and Local level (Source: 2021 and 2011 ACS 1-Year Estimates)

According to the *Market Rate Housing Needs and Supply Analysis* assembled by Washington-based consultancy BERK and commissioned by the City of Seattle in April 2021, despite a significant surge in building new housing units, supply is still not meeting demand. This is due primarily to being outpaced by the rate of new employment opportunities in the city. In other words, Seattle has been unable to maintain its jobs to housing unit ratio. This scarcity of housing ultimately increases competition, rents, and housing prices in the market overall.

For the purposes of this analysis, the City of Seattle is divided into 7 market areas: North, North Central, West Central, East Central, Greater Downtown, Southwest, and Southeast (Figure 5).

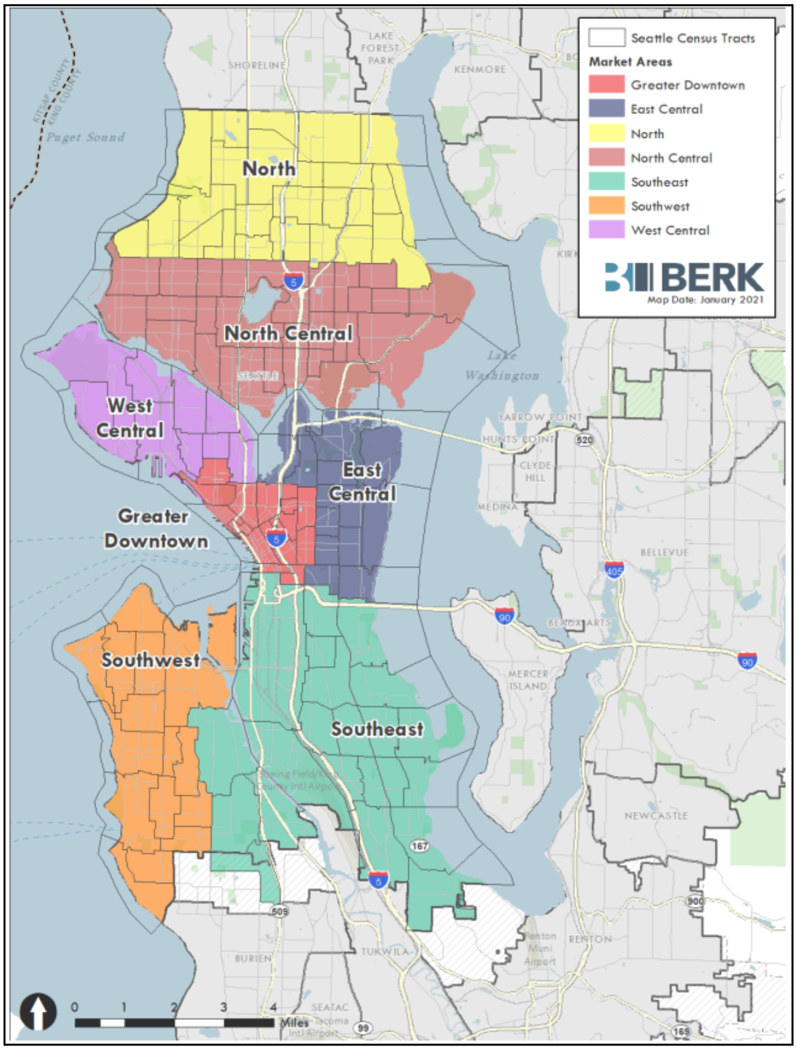


Figure 5: Seattle Market Areas (Source: BERK, Exhibit 23 in Native Analysis)

Housing Inventory

Of the nearly 370,000 housing units within the bounds of Seattle, a majority of housing units are classified as either detached single family or apartment units. *Table 7* below shows the breakdown of housing unit type across the seven market areas delineated. As seen in the table below, nearly 80% of all housing units are either single family homes or apartments while low to middle density housing categories encompass a much smaller percentage.

Unit Type	Greater Downtown	East Central	West Central	North	North Central	Southwest	Southeast	Total
Total	**82,112**	**35,084**	**29,022**	**54,712**	**83,193**	**40,354**	**45,292**	**369,772**
Percentage by unit type								
Detached Single Family*	0.8%	34.2%	37.6%	49.1%	42.4%	53.1%	59.6%	36.3%
Multifamily housing types:								
Duplex	0.3%	4.0%	3.3%	1.6%	3.8%	2.2%	2.2%	2.3%
Triplex	0.2%	1.8%	2.1%	1.0%	1.9%	1.0%	1.0%	1.2%
4-Plex	0.3%	1.7%	1.4%	0.9%	1.1%	1.3%	1.2%	1.0%
Townhome	0.7%	8.3%	4.9%	5.6%	5.6%	7.1%	6.2%	5.0%
Condominium	17.1%	10.5%	12.6%	7.1%	6.6%	7.8%	3.0%	9.5%
Apartment	78.2%	38.0%	36.3%	33.0%	37.2%	25.8%	25.6%	43.0%
Senior Housing**	2.1%	1.4%	1.5%	1.7%	1.3%	1.7%	1.1%	1.6%
Other***	0.3%	0.2%	0.2%	0.0%	0.0%	0.0%	0.0%	0.1%

*Detached Single Family includes some accessory dwelling units as the King County Assessor does not track ADUs/DADUs separately.
**Senior Housing includes properties classified as "Retirement Facilities" and does not include nursing homes.
***Housing Units classified as "other" include unique residences such as houseboats and caretaker quarters.

Table 7: Total Housing Units by Type and Market Area (Source: BERK, Exhibit 24 in Native Analysis)

As seen in *Table 7* above, the City of Seattle does not have a wide variety of housing typologies in the city currently. A majority of owner-occupied housing units are single-family homes, whereas a majority of renter-occupied housing units are in multi-family buildings with 20+ units (primarily 50+ units). This has contributed to the lack of availability of housing options for lower income households as is discussed further in Section 4 of this thesis. A 2016 report jointly prepared by the City of Seattle's Office of Housing and Office of Planning & Community Development found that units in medium to large apartment complexes are both the most common form of rental units in Seattle and also more expensive to rent at 103% of AMI. On the other hand, units in small apartment complexes typically only require 79% of AMI on average to afford. However, these smaller complexes are few and far between in the City (City of Seattle Office of Housing & City of Seattle Office of Planning & Community Development, 2016).

In a 2016 survey conducted by the City of Seattle to understand the average 1-bedroom gross rent by neighborhood market area for medium to large apartment complexes (20+ units), it was found that there is a significant difference in rental price of a 1 bedroom apartment across the city *(Figure 6)*. This variance can be mostly attributed to age of unit and proximity to employment zones. Looking at *Figure 6,* we can see that average rents in Belltown/Downtown/South Lake Union (in dark orange on the map below) are the most expensive in the area at $2,170/month for a 1 bedroom apartment. This is largely due to the fact that most of the housing in this area was constructed recently and the proximity to jobs is a significant draw. While average 1 bedroom rents in Capitol Hill/Eastlake are also expensive at $1,756/month, this difference in rent prices is influenced by a large amount of older rental properties (City of Seattle Office of Housing & City of Seattle Office of Planning & Community Development, 2016).

1-Bedroom Gross Rents by Neighborhood Market Area
Medium to Large Apartment Complexes (20+ units)
Seattle, Fall 2016

Dupre + Scott Neighborhood Market Area	Surveyed Properties	Surveyed Units	Average Gross Rent in Fall 2016
Total:	883	33,625	$1,752
Ballard	30	1,923	$1,821
Beacon Hill	10	244	$1,284
Belltown/Downtown/ South Lake Union	97	7,096	$2,170
Capitol Hill/ Eastlake	175	4,275	$1,756
Central	42	1,211	$1,720
First Hill	66	2,480	$1,814
Green Lake/ Wallingford	62	2,332	$1,804
Madison/Leschi	6	295	$1,458
Magnolia	20	698	$1,522
North Seattle	110	4,479	$1,328
Queen Anne	106	3,735	$1,770
Rainier Valley	19	728	$1,374
Riverton/Tukwila*	2	37	$763
University	72	1,671	$1,519
West Seattle	60	2,201	$1,578
White Center	6	220	$1,387

Source: Custom data tabulations from D +S fall 2016 rent survey data. Estimates reflect rent plus estimated cost of tenant-paid utilities.

*Survey data for the portion of Riverton/Tukwila with Seattle are limited to two properties and should be interpreted with caution.

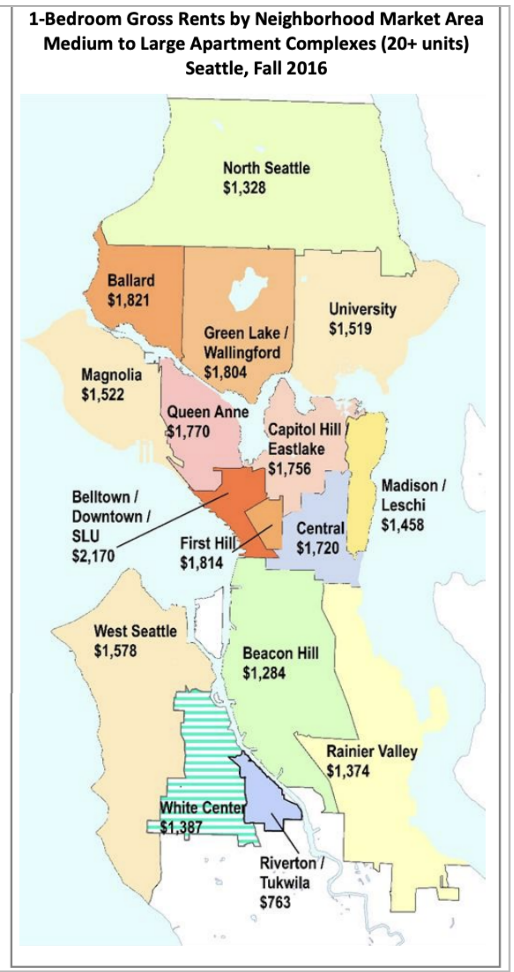


Figure 6: Average rents by Neighborhood for 1-bedroom units in 20+ unit complexes (Source: City of Seattle)

Housing Capacity

The State of Washington's Growth Management Act (GMA) requires that local jurisdictions must conduct a thorough inventory and analysis of the current state of housing as well as projected housing needs during the development of a comprehensive plan. This analysis is assembled by primarily leveraging

American Community Survey Data (ACS) prepared by the US Census Bureau for the US Department of Housing and Urban Development (HUD). Within the data collected as a part of ACS, HUD receives custom tabulations known as "CHAS" data (Comprehensive Housing Affordability Strategy) that measures the extent of housing insecurity in an area - particularly for low income households. CHAS data has been utilized by the City of Seattle in order to distill an understanding of metrics such as household income, housing cost burden, and measuring the affordability of Seattle's housing supply.

Growth is estimated in Seattle through a partnership between the King County Growth Management Planning Council and the Washington State Office of Financial Management (OFM). The OFM forecasts population growth on a county basis, after which King County converts population growth into housing units to better manage. For Seattle, the twenty-five-year housing growth allocation was 86,000 net new housing units (Seattle 2035, 476). This projection is then reviewed against the GMA-required buildable lands report, a document prepared that essentially audits the current housing status and estimates the amount of further development that could occur within the constraints of existing development rules.

The City's Department of Planning and Development (DPD) defines development capacity (also known as zoned development capacity or zoned capacity) as an estimate of how much new development could be built over time, given current zoning conditions. Residential development capacity is expressed as a number of housing units. To track this, Seattle's Office of Planning & Community Development (OPCD) built a development capacity model based on land parcel information from the King County Department of Assessments. This model uses the following general methodology to calculate the development capacity of King County neighborhoods:

Step 1: Land Available = Vacant Parcels + Underdeveloped Parcels - Excluded Parcels
Step 2: Potential Development = Developable Land Area x Future Density Assumption
Step 3: Development Capacity - Potential Development - Existing Development

According to the September 2014 Development Capacity Report prepared by the DPD, Seattle has adequate capacity to add about 224,000 housing units and 232,000 jobs. This capacity exceeds projections in the 2035 Comprehensive Plan where the City calls for the need to accommodate 70,000 households over the next 20 years. When looking at the capacity by zone, Seattle has the most housing development capacity in neighborhood commercial, downtown, and low rise residential zones (City of Seattle Department of Planning and Development, 2014).

Current Housing Growth

The City of Seattle's Housing Growth Report *(Figure 7)* documents the amount of housing the City has planned for and executed on within the last 10 years. Since 2015, Seattle has built over 60,000 housing units, has 24,000 units under construction, and has another 8,000 units permitted through Q4 of 2022. The report also tracks the new housing unit built by type (i.e. single family, multi-family, and mixed-use) and the demolished housing by unit type. Over the last decade, Seattle has demolished over 3,500 single family housing units and built over 45,000 housing units within mixed-use developments.

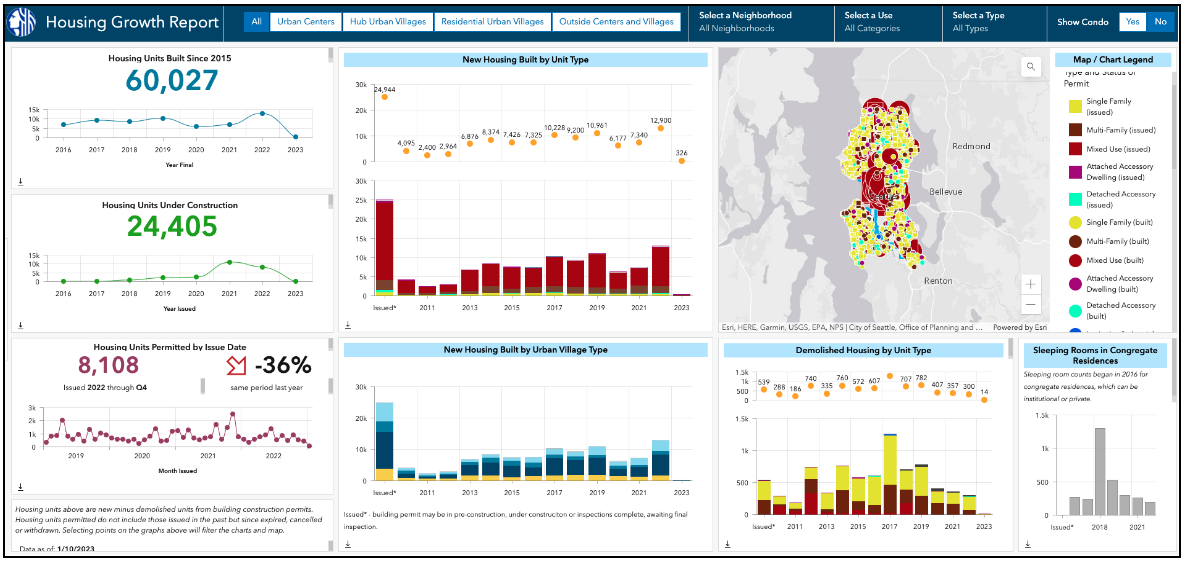


Figure 7: Housing Growth Report (Source: The City of Seattle)

A majority of new housing units in Seattle are built in the form of mixed-use and multi-family units. Last year in 2022, of 12,800 total housing units developed in Seattle, 10k units were mixed-use and 1.8k units were multi-family.

The Seattle Office of Planning and Community Development (OPCD) utilizes the *Urban Village framework* to describe a zoning strategy that enables the City to "deliver services more equitably, pursue a development pattern that is environmentally and economically sound, and provide a better means of managing growth and change through collaboration with the community in planning for the future of these areas" (OPCD, 2005). There are four urban village categories: (1) Urban centers, and the urban villages within them, are intended to be the densest areas with the widest range of land uses, (2) Hub urban villages accommodate a broad mix of uses but at lower densities than Urban centers, (3) Residential urban villages are predominantly residential development around a core of commercial services, and finally (4) manufacturing/industrial centers are intended to maintain viable industrial activity and promote industrial growth and development.

This urban village strategy is utilized to inform and influence the City of Seattle's urban growth patterns, directing jobs and new housing development to urban centers where connectivity to transit and compact urban living already exists. When projecting growth to 2035, OPCD has allocated a majority of the housing unit and job growth to the six urban centers (Downtown, First Hill/Capitol Hill, South Lake Union, Uptown, University District, and Northgate) as shown in *Table 8* below.

Location	Housing Units	Job
	Urban Centers	
Downtown	10,000	30,000
First Hill/Capitol Hill	7,000	4,000
South Lake Union	4,700	20,000
Uptown	3,500	3,500
University District	2,700	8,000
Northgate	1,600	5,000
	M/I Centers	
Duwamish		3,000
Ballard/Interbay		1,500
Remainder of city (Urban Villages and areas outside centers/villages)	40,500	40,000
Total	**70,000**	**115,000**

Table 8: Growth Estimates for Urban Centers and Manufacturing/Industrial Center (Source: Seattle OPCD)

When cross-referencing the Housing Growth Report, it seems that the City of Seattle is actually exceeding growth expectations in these urban centers. Since 2015, Seattle has built over 30,633 housing units in urban centers and has more than 11,000 units under construction. The overwhelming majority of housing units are located within mixed use developments.

Housing Summary

In conclusion, housing in Seattle is a complex subject. For one, housing prices and distribution of housing typologies vary throughout the city - similar to other populous and economically thriving cities. The City of Seattle uses a variety of different geographic strategies (such as the Urban Village model) to divide the city into areas to prioritize location of housing and new employment opportunities. Secondly, the development capacity is expected to suffice for projections laid out by the Seattle 2035 Comprehensive Plan. This indicates that there is room for the growth that the city is bound to encounter. Finally, to date Seattle has been building housing that meets the pace needed to accommodate growth projections. However, escalating housing costs has resulted in increased unaffordability for households that fall below Area Median Income. The effects of these conditions will be discussed in greater detail in Section 4.

Section 4: Affordability in Seattle

Unaffordable Conditions

Given the rapid population growth in Seattle over the last decade, the City experienced a housing market boom that resulted in escalated home prices and rent. These conditions are felt even more strongly for households that are making below the area median income (AMI) and have positioned low income households at a risk for displacement. The City of Seattle identifies housing cost burden and shortage in affordable and available rental housing as two key indicators of "economic displacement and exclusionary neighborhood change" (Seattle Office of Planning and Community Development, 2023).

Housing Cost Burden: Based on the definition stated in the introduction that households spending more than 30% of their income on housing are considered "cost burdened", it is estimated that 25% of Seattle homeowners and 44% of renters were cost burdened in 2018 (Seattle Office of Planning and Community Development, 2023). Similar to national patterns of housing cost burden, households of color and extremely low income/very low income households experience a significantly higher cost burden with rising costs of housing than households closer to AMI.

Availability and Affordability of Rental Housing: The supply of rental housing units to households across the income spectrum is diverging in Seattle. While middle-and upper income (100-120% AMI) households are gaining more access to rental housing affordable to them, unit supply has drastically decreased for units affordable to lower-income households. In fact, of the units that are affordable to lower income households, a substantial proportion of those are being rented by higher-income households. This has resulted in a severe shortage of units both available and affordable to low-income households in Seattle. As shown in Figure 8 below, the shortage of rental property increases in severity as household income decreases. For every 100 households below 50% of AMI, there are only 40 units available. For those households who have extremely low incomes (30% of AMI or less), the number of units drops to 34.

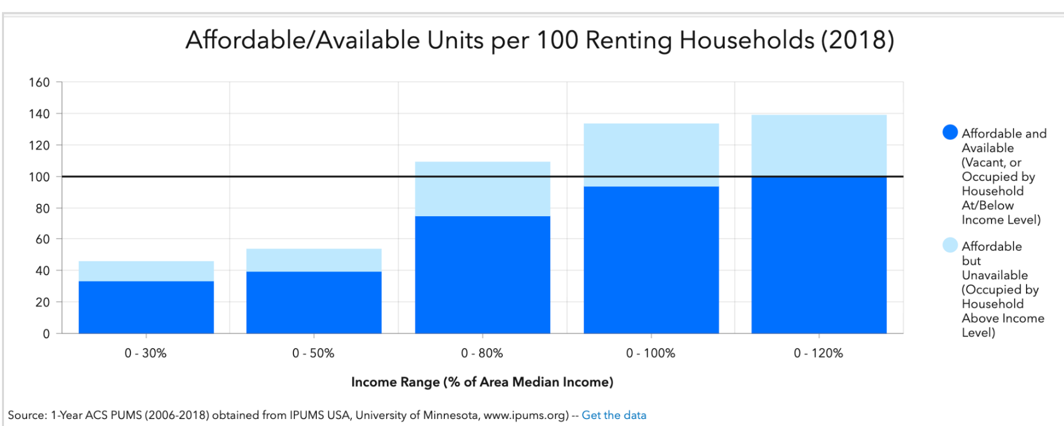


Figure 8: Affordable/Available Units per 100 Renting Households (Source: The City of Seattle, 2018)

2035 Seattle Comprehensive Plan

Recognizing current unaffordable conditions, Seattle's comprehensive plan is grounded in the vision that "all people have access to housing that is safe, clean, and affordable" (Seattle 2035, 96). The document highlights that volatility in housing prices is a key contributor to economic inequality and is disproportionately affecting marginalized populations. In a study investigating the *Share of Seattle Households Who Are Severely Housing-Cost Burdened by Race/Ethnicity of Person who Owns or Rents a Home*, it was found that about 22% of households of color and about a third of Black households are considered to be severely housing-cost burdened (Seattle 2035, 97). The City has deemed it to be critical to address social equity through the development and preservation of affordable housing. The comprehensive plan aims to achieve the goal of expanding affordable housing options through five key topic areas: **Equal Access to Housing, Supply of Housing, Diversity of Housing, Housing Construction and Design, and Housing Affordability.**

Across these topic areas, the City has identified particular strategies and policies to increase affordable housing that relate to the design and construction of the housing structure itself:

Equal Access to Housing:

1. Support the development and preservation of affordable housing in areas with a high risk of displacement through tools and actions such as land banking, public or non-profit acquisition of affordable buildings, and new affordable and mixed-income development.

Housing Affordability:

1. Encourage a shared responsibility between the private and public sectors for addressing affordable housing needs.
2. Continue to promote best practices in use of green building materials, sustainability, and resiliency in policies for rent/income-restricted housing.
3. Encourage and advocate for new federal, state, and county laws, regulations, programs, and incentives that would increase the production and preservation of lower-income housing.

Housing Construction and Design:

1. Encourage innovation in residential design, construction, and technology, and implement regulations to conserve water, energy, and materials; reduce greenhouse gas emissions; and otherwise limit environmental and health impacts.
2. Explore ways to reduce housing development costs.

Diversity of Housing:

1. Encourage the development of family-sized housing affordable for households with a broad range of incomes in areas with access to amenities and services.
2. Promote use of customizable modular designs and other flexible housing concepts to allow for households' changing needs, including in areas zoned for neighborhood residential use.
3. Allow additional housing types in neighborhood residential areas inside urban villages; respect general height and bulk development limits currently allowed while giving households access to transit hubs and the diversity of goods and services that those areas provide.

The city has outlined a few policies that they plan to follow in order to help achieve the primary goal of meeting both current and future housing needs of all residents through increasing housing supply:

1. Allow and promote innovative and nontraditional housing design and construction types to accommodate residential growth.
2. Consider Land Use Code and Building Code regulations that allow for flexible reuse of existing structures in order to maintain or increase housing supply, while maintaining life-safety standards.
3. Encourage use of vacant or underdeveloped land for housing and mixed-used development, and promote turning vacant housing back into safe places to live.
4. Monitor the supply of housing and encourage the replacement of housing that is demolished or converted to nonresidential or higher-cost residential use.
5. Evaluate the City's efforts to mitigate displacement of affordable housing.

Affordable Housing Programs in Seattle

There are a variety of different programs that the City of Seattle leverages to fund and regulate affordable housing. These programs are described below:

- City Funded: Housing built under the "City Funded" program is through direct capital investment by the Seattle Office of Housing for the purpose of building affordable homes. Funding typically is obtained from sources like housing levies, MHA and Incentive Zoning payments, bond proceeds, and federal funds such as the Low Income Housing Tax Credit.

- Multifamily Tax Exemption (MFTE): The MFTE program exempts property tax on residential improvements to owners of multifamily rental buildings in exchange for owners allocating at least 20% of building units as affordable. This program lasts up to 12 years.

- Incentive Zoning (IZ): The IZ program encourages commercial and residential real estate developers to unlock additional city-granted development capacity in exchange for building affordable housing units (performance option) or making a payment to help fund affordable housing (payment option). Performance IZ housing units are guaranteed to remain affordable for 50 years.

- Mandatory Housing Affordability (MHA): The MHA program is set up in a similar structure to the IZ program, offering two options for developers to either build affordable housing as part of greater development plans or contribute to a fund that aims to preserve and produce affordable housing. MHA payments contribute significantly to the City Funded housing units described above.

Figure 9 below shows the change over time of city-regulated affordable housing stock in Seattle. As of 2023, there are 28,327 affordable housing units, of which 7,000 are City Funded (denoted at existing Seattle Housing Authority properties) and 20,914 are regulated through the MFTE, IZ, and MHA programs described above.

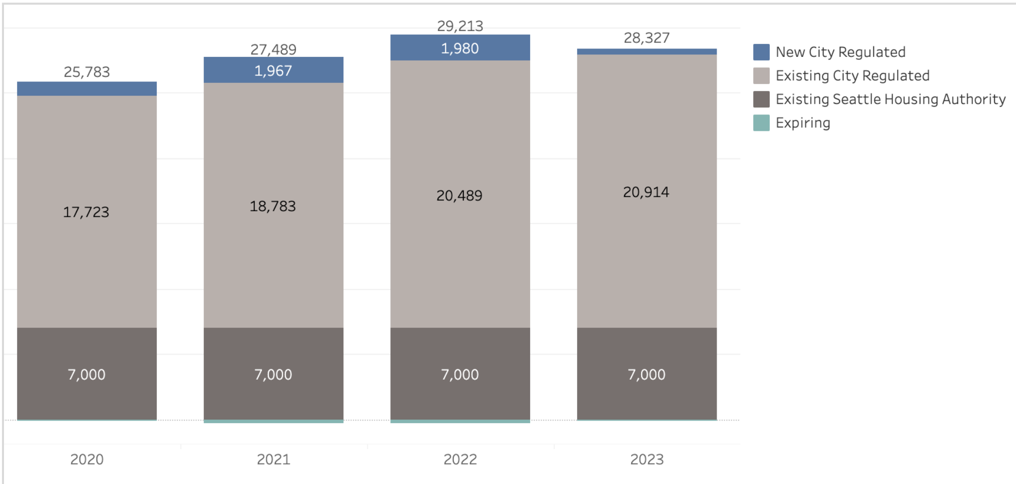


Figure 9: Existing Affordable Homes (Source: The City of Seattle)

Looking at the future, there are 12,756 housing units and 105 buildings currently under development. Of these structures, there are 5,553 affordable housing units coming online and a majority of these properties are supported by City Funded programming or through the City Multifamily Property Tax Exemption program (Figure 10).

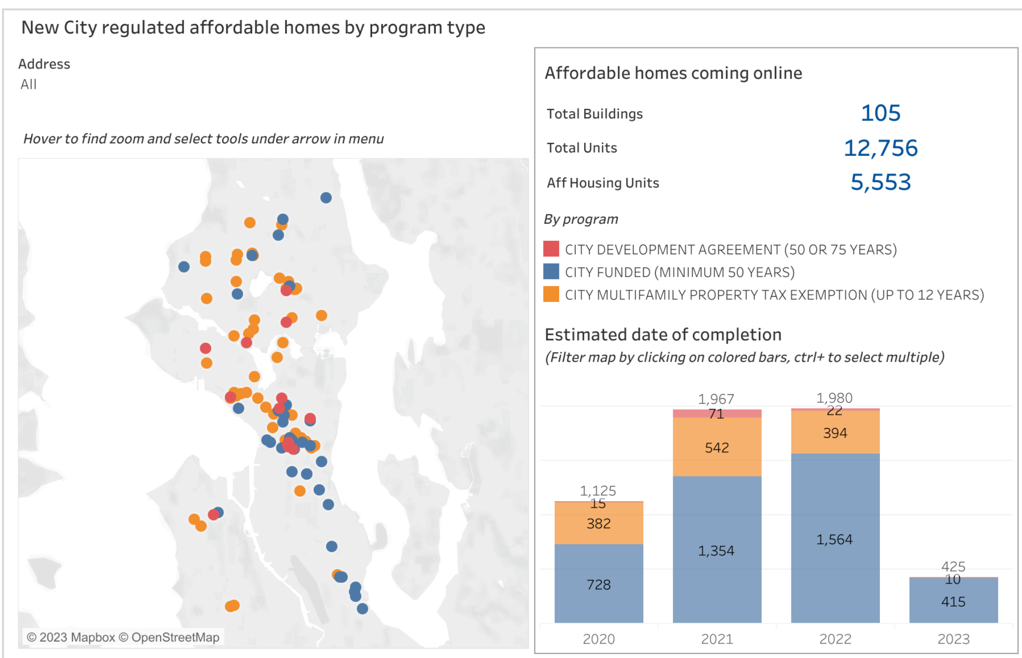


Figure 10: New City-Regulated Affordable Homes by Program Type (Source: The City of Seattle)

However, in order to support the needs of low income families, the City will need to use innovative solutions to build less expensive affordable housing through increased efficiency. The method this thesis explores is through leveraging construction technology.

Section 5: Construction Technology

As discussed in the Introduction, the field of Construction Technology has emerged greatly from 2010 to today. The industry has evolved from integrating technology for streamlining project management as utilized in other industries, to construction-specific enhancements such as safety assisting and increased field productivity. In a 2020 report produced by McKinsey and Company, over 2,400 construction technology companies were mapped to develop a visualization of the current use cases. Shown in Figure 11 below, primary industry focus clusters included 3-D printing, modularization, and robotics-enabled technologies.

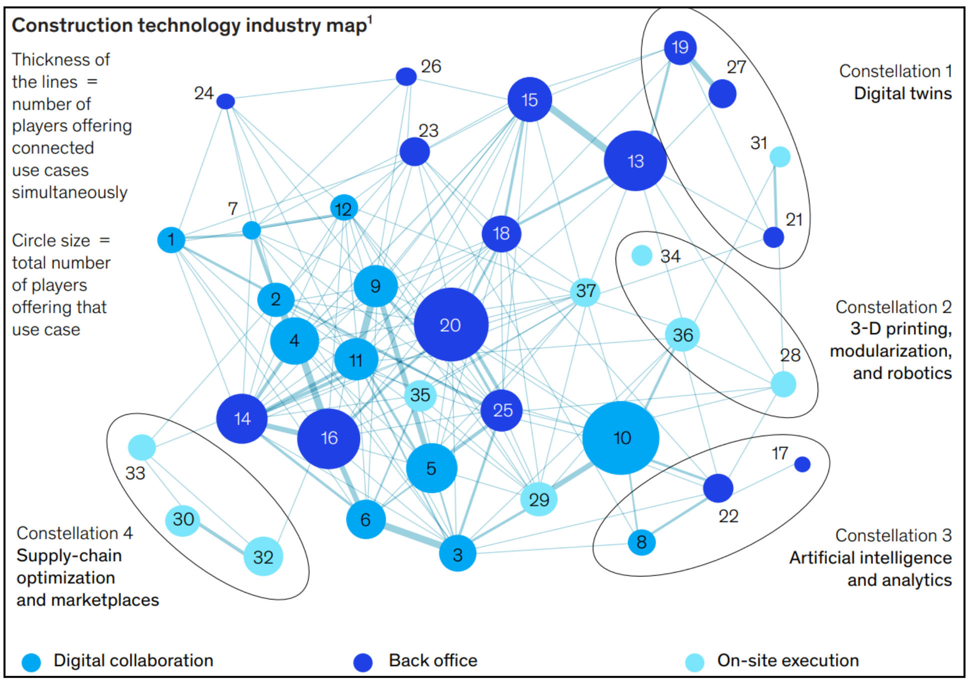


Figure 11: Construction Technology Industry Map (McKinsey and Co. 2020)

McKinsey categorizes these innovations into three primary scenarios where construction technology can be deployed: 1) on-site, 2) back office, and for 3) digital collaboration. Technologies designed for on-site utilization address the unique challenges that are faced on a construction job site such as low productivity and material delays. Examples of on-site technologies are 3-D printing, off-site fabrication, and robotics. Back office innovations often address concerns of project disorganization and can appear in the form of data management, financial automation, and real-time schedule development. Technologies implemented in the back office often take the form of 3-D modeling, laser scanning, machine learning, and document management. Lastly, with the number of professionals needed from the start to finish of a construction project, it is important to find effective ways to communicate and collaborate digitally. Technology that tracks design development, manages contracts and project-specific documents, and streamlines field work to share progress on site all help when ensuring the disparate project team is aligned. Examples of these technologies include predictive assessment performance, equipment management, and digital estimating.

With the onset of the Covid-19 pandemic, the construction industry was forced to rapidly innovate at a pace that hadn't been seen before. In 2020, Commercial real estate and property investment firm JLL developed the *State of the Construction Technology Report* to document the effects of the pandemic on the construction industry. The report ranks construction technology categories by how the pandemic has boosted growth, and assigns technologies to a level of perceived impact *within the constraints posed by the pandemic:*

▲ High impact	— Moderate impact	▼ Low impact
• Digital collaboration	• Drones	• Equipment/materials
• Scanning	• Jobs/employment	• Payment/finance
• Safety/wearables	• Robotics	• 3d-printing
• Bim/cad	• Augmented/virtual reality	• Artificial intelligence
	• Digital twins	• Modular construction

Table 9: Pandemic-accelerated Construction Technology Impact Matrix (JLL 2020)

Construction technologies such as scanning, safety technologies, and Building Information Modeling (BIM), are poised to result in high impact benefits when utilized on a project that involves pandemic stresses. With construction personnel being categorized as essential workers, concerns of safety were top of mind as the site crew were exposed to daily health risks. Digital collaboration became more of a necessary component for working remotely during a pandemic, and as such technologies that enable digital collaboration have solidified their place as a core component of any new construction project today. Similarly, BIM continues to be a technology that has unlocked design development throughout the construction process. Increased capabilities in BIM software packages have enabled more sophisticated coordination of trades, especially necessary during the pandemic.

Construction Technology Hierarchy

JLL describes their construction technology hierarchy as a tool to "understand construction tech particularly who are prioritizing adoption and investment in new tools" (D'Esposito, 2020). As depicted in the diagram below, there are three primary ways of categorizing these technologies. First, a foundational technology is applied to technologies that are both commonplace (readily available across all budgetary constraints) and necessary for utilizing more complex technologies. Foundational technologies include 1) BIM & CAD, 2) Digital Twins, 3) Artificial Intelligence and 4) Digital Collaboration. Next, there are Primary Impact technologies which are innovations that have developed to a higher fidelity level than other secondary impact technologies. Finally, secondary impact technologies include emerging technology solutions that are low fidelity and early in development as well as technologies that have incremental impact. This hierarchy is depicted in Figure 12 below.

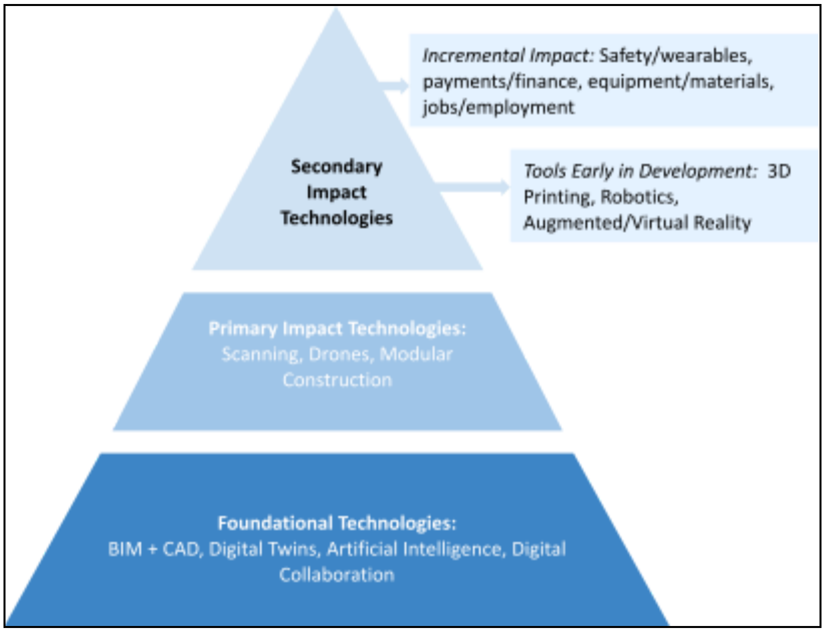


Figure 12: Construction Technology Hierarchy (JLL 2020), Diagram: Harshita Pilla

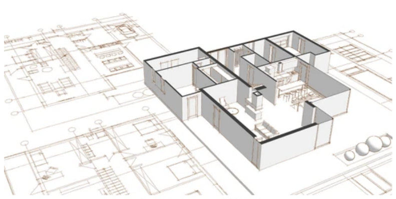
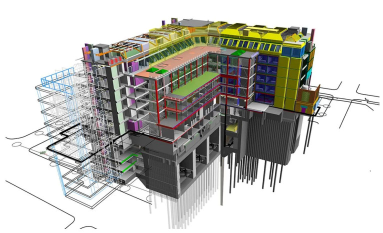
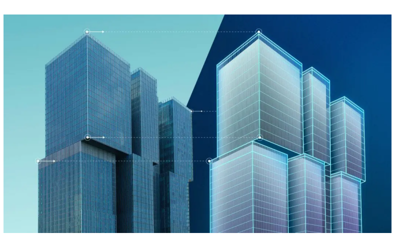
Foundational Technologies

The five technologies that are classified by JLL as foundational are (1) Computer Aided Design (CAD), (2) Building Information Modeling (BIM), (3) Digital Twins, (4) Artificial Intelligence, and (5) Digital Collaboration. BIM and CAD technologies were developed in the 1970s and 1980s through advancement in digital drawing software and specifically advancements in modeling constructive solid geometry (CSG) and boundary representation (Quirk, 2012). Gábor Bojár would later go on to found ArchiCAD in 1984, which would make ArchiCAD the first BIM software available on a personal computer. The technology became more widely utilized in the early 2000s and now has reached the "mass-adoption stage in the U.S." with over 98% of large architecture firms in the country designing with BIM on their projects (Bradley, 2021).

Digital Twins refer to a more sophisticated iteration of BIM and CAD where construction and design projects have an exact digital replica of the physical project. This full virtual model can be leveraged for scenario planning needs and closeout documentation during the construction process but also for maintaining building operations after the project is completed. Building a digital twin typically requires a multitude of technologies such as BIM, sensors, and artificial intelligence. This technology is utilized primarily for larger markets.

Artificial intelligence (AI) is a term used to describe the "simulation of human intelligence processes by machines" and has been recently utilized in the construction industry to identify areas for efficiency and increase site productivity (Burns, 2022). Current deployment of AI technology in construction is focused on improving project planning activities such as predictive scheduling, isolating cost overruns, prioritizing issues to handle on site. A core component of AI technology are machine learning (ML) algorithms that map and automate human decision making. ML can be incorporated into other technologies such as scanning, robotics, and BIM and is considered foundational for its widespread use and application to other emerging construction technologies (Rao, 2022).

The final foundational technology in JLL's construction technology hierarchy is Digital Collaboration. This term refers to a suite of cloud-based products that enable all project team members to access project documentation and update in real-time. This technology is critical to project management and organization and is ubiquitous in the architecture, engineering, and construction (AEC) industries today. These technologies have the greatest maturity amongst other foundational technologies within the construction technology industry. These foundational technologies are summarized in *Table 10* below with a short description as well as notable companies that currently bring the technology to market.

Foundational Technologies		
Technology	**Description**	**Notable Companies**
Computer Aided Design (CAD) 	A way to digitally create 2D drawings and 3D models of real-world products before they are built. 3D CAD enables design sharing, review, and modification easily.	Autodesk (AutoCAD) Dassault Systemes PTC Inc Siemens Hexagon PPM Bentley Altium Encore BricsCAD
Building Information Modeling (BIM) 	The foundation of digital transformation in the architecture, engineering, and construction industry (AEC). Describes tools for creating and managing information for a built asset.	Autodesk Revit Plannerly Trimble Connect Revizto BIMCollab Dalux ("Top Manufacturing Engineering CAD Vendors | CADTalk," n.d.)
Digital Twins 	Digital twins are used in construction projects to create exact replicas of real-world spaces. These 3D models allow construction teams to interact virtually with the physical property during the design and planning stages (Matterport, 2022).	Autodesk Matterport Oracle ENGworks StructionSite
Artificial Intelligence (AI)	AI technology can be leveraged within the construction industry to refine quality control, streamline	Alice Technologies Doxel Built Robotics

	claims management, boost project monitoring, aid in risk management, and constantly optimize design (Blanco, Fuchs, Parsons, & Ribeirinho, 2018).	SmartVids
Digital Collaboration 	Digital Collaboration platforms help unify communication and collaboration in construction, ensure data is always available and that project documentation is up to date.	Procore Box Bluebeam Autodesk Fieldwire Newforma Oracle

Table 10: Foundational Construction Technologies Summary

Primary Impact Technologies

JLL categorizes "primary impact" technologies as those innovations that are anticipated to have the greatest overall impact on the construction industry in the imminent future. These technologies are more mature in development than secondary impact technologies, but not quite as universally incorporated on projects as the foundational technologies described previously. JLL identifies three key technologies that fall into this category: (1) Scanning, (2) Drones, and (3) Modular Construction.

Laser Scanning, also known as high-definition surveying (HDS) or reality capture, is a construction technology that is utilized for rendering an accurate 3D model of a project site. This geolocational data is rendered using BIM technology and referred to as a "point cloud". Scanning can be utilized throughout a project life cycle to aid in process documentation, progress capture, and memorializing final built conditions. During the construction process, laser scans help significantly with facilitating coordination between different trades as well as identify conflict areas/errors in the building process faster. Some of the challenges associated with laser scanning are the expense related with laser equipment rental and the laser technician.

Drones are another primary construction technology identified by JLL. A drone is an unmanned aerial vehicle (UAV) that can be controlled remotely from a user or a software application. While drones have historically been used for military and aerospace industries, they were introduced to the construction industry to reduce costs associated with labor to complete land surveys, mapping, equipment tracking, and progress reporting on site. Since drones have such a wide coverage, the technology is capable of surveying vast acres of land in just 15-30 minutes, which saves up to 20x the cost of topographic maps. Additionally, drones can help track equipment, safety, and progress on a job site (BigRentz, 2022). In the future, drones are expected to integrate with AI technology to direct and guide construction equipment on site (Passley, 2022).

The last technology within JLL's primary impact category is Modular Construction. This construction technology "involves producing standardized components of a structure in an off-site factory, then assembling them on-site" (Bertram et al., 2019). The technology first became popular during post war times in the United Kingdom and the United States, but saw a resurgence in popularity since the early 2000s. By producing modules off-site, a project could reduce total schedule duration, labor needs, and amount of rework needed. All of these efficiencies can significantly increase cost savings on a project site. Modular construction is relatively capital intensive and requires a lot of off-site construction space, which can pose a problem in space-constrained urban environments. Primary impact technologies are summarized below in *Table 11.*

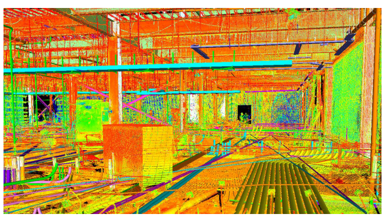
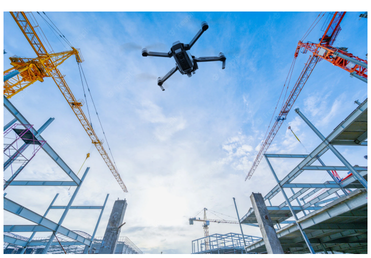
Primary Impact Technologies		
Technology	**Description**	**Notable Companies**
Laser Scanning 	Utilizing a high-definition laser to map an area and develop a "point cloud" database. 3D building scans can help with accurate site design, coordinating trades for construction activities, and provide as-builts for end project documentation (Ellis, 2022b).	Matterport OpenSpace Disperse.io Leica Geosystems StructionSite Hexagon Autodesk NavVis Artec 3D Scanners
Drones 	Drones or Unmanned Aerial Vehicles (UAVs) are utilized as a construction technology for aerial documentation of a project site. Drones are leveraged to track project progress as well as ensure worker safety.	ZenaDrone 3D Robotics Airware DroneDeploy Intel Hangar PrecisionHawk Trimble Skyward (Wood, 2017)
Modular Construction 	Modular Construction is a term to describe the process where modules are designed and built off-site and then brought to a jobsite to be assembled. This innovation aims to reduce complexities of on-site building and accelerate project schedule.	Katerra Stack Modular Bird Construction Prescient Project Frog ANC Modular Due North Housing ED Modular Blokable

Table 11: Primary Impact Construction Technologies Summary

Secondary Impact Technologies

The final level of JLL's construction hierarchy are the secondary impact construction technologies. These innovations are classified into two categories: 1) technologies with a total impact that is more incremental and 2) tools that are projected to have significant impact to the industry but are currently low fidelity. Key incremental impact technologies that were identified are 1) Equipment/Materials, 2) Safety/Wearables, 3) Payments/Finance, and 4) Jobs/Employment. Finally, low maturity technologies such as 3D printing, robotics, and augmented/virtual reality were identified by JLL as secondary impact.

Incremental Impact Technologies

The process of purchasing/renting equipment and materials is often quite burdensome and administratively intensive. Platform technology is being utilized in this space to develop online marketplace environments for this exchange of goods. A downstream impact of further developing this software is the environmental benefits from reutilizing materials and lowering overall production costs of operating excessive equipment. This technology is considered incremental in impact because its scale is constrained to the size of the job site and the materials and equipment needed for the project.

Safety is of utmost importance on a construction site and has been a long-time industry priority given the physical nature of the work. Furthermore, the coronavirus pandemic really exacerbated this need with construction workers determined to be "essential workers". A variety of technologies have been incorporated in safety procedures to ensure workers are protected from injuries and fatalities. One of the primary ways construction technology is being incorporated into safety is through wearables such as smart watches, exoskeletons, powered footwear, smart helmets, and Augmented Reality (AR) glasses (Stannard, 2020). Wearable technology assists in detecting collisions, predicting unsafe behaviors, and tracking workers.

Another use case for implementing financial platform technology is within the construction industry. Having to manage cash flows in and out of a project and between a multitude of stakeholders is complicated and requires a lot of time to sort through. Fin-tech solutions that help automate payments, streamline loan applications, and track project financing are being increasingly utilized in construction project management (Scalisi, 2021). These technologies are particularly helpful in increasing efficiency in a contractor's back-office workflow.

The last technology that JLL identifies as an incremental secondary impact technology are digital employment platforms. Similar to the technology utilized in creating shared marketplaces for equipment and material exchanges, digital employment platforms leverage technology to connect employers to job seekers. While this technology is not the highest impact, it is important in addressing current labor shortage concerns in the industry (Brusco, 2021).

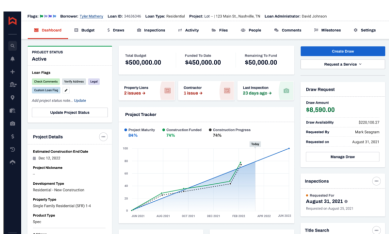
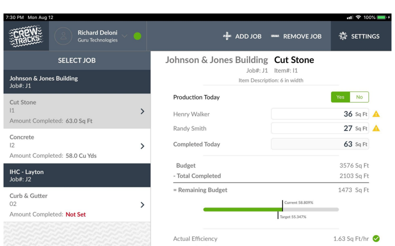
Secondary Impact Technologies - Incremental		
Technology	**Description**	**Notable Companies**
Equipment/Materials 	Utilizing digital platforms to create a marketplace for exchanging equipment and materials between project sites.	EquipmentShare RenoRun
Safety/Wearables 	Wearable technology can help increase safety on a construction site by monitoring vitals to prevent overexertion, detecting edges to prevent falls and collisions.	Triax Technologies WakeCap SuitX SolePower Caterpillar Smartband Trimble XR10 with HaloLens 2 Spot-r clip SmartCap ("Top Construction Wearables of 2021," 2021)
Payments/Finance 	Fin-tech technologies such as payment management, automation, and secure project financing are being utilized within construction to streamline cash flow management.	Billd Built Briq Procore Levelset Rabbet Land Gorilla
Jobs/Employment 	Utilizing digital platforms to create a marketplace for connecting workers to construction employment opportunities.	TradeHounds Core (Aka Crews by Core) Propeller Platform

Table 12: Incremental Secondary Impact Construction Technologies Summary

Technologies Early in Development

In the final category of the Construction Technology hierarchy, JLL identifies three technologies that have the potential to radically change the construction industry but are low in maturity relative to the other technology areas described within the hierarchy. Robotics, 3D Printing, and Augmented Reality/Virtual Reality (AR/VR) are three technologies that have seen a lot of growth in the sector over the last 5 years.

Robotics

Robotics technology has gotten a lot of attention as a key growth area for the construction industry. Robotics refers to the design, construction, operation and utilization of "autonomous machinery capable of sensing its environment, carrying out computations to make decisions, and performing actions in the real world" (Guizzo, 2018). The global construction robotics market size was valued at 50 million USD in 2021 and is expected to exceed 160 million USD by 2030, with a compound annual growth rate (CAGR) of 14% (Straits Research, 2022). The industry is shifting towards adoption of this technology because robotics have enabled enhanced productivity, safety, and quality on the job site. There are a variety of ways that robotics technology can integrate within current construction processes to drive efficiency:

1. Labor: With labor retention becoming an increasing issue within the construction industry, robotics technology can help offset labor shortages through automation of repetitive tasks on site such as layout, framing, painting, and foundation setting. Boston Dynamics' Spot is a robot that aids in site progress monitoring through autonomous capture, BIM model comparison, digital twin creation, and site surveying to improve worker health and safety. The HP SitePrint is another technology utilizing robotics to streamline the layout process on site.

2. Safety: Construction labor retention also requires that job sites be designed to support worker safety. Robotics can play a huge role in developing safety-focused support technologies for field workers. Exoskeletons are examples of this, where robotics are used to build suits to support workers while performing strenuous tasks such as lifting, hanging, loading, and drilling. Exoskeletons are meant to assist workers and prevent injuries from overexertion on site (Thilmany, 2019).

3. Environmental: Construction sites are environments where a lot of waste is generated and with robotics technology, extra task precision leads to less material waste on site. Additionally, robotics can be powered by clean energy sources which also contribute to an overall more environmentally conscious jobsite. Finally, by utilizing robotics technology to contribute to off-site building processes such as 3D printing and prefabrication, projects are able to control environmental exposures to laborers and be more energy efficient overall (Long, 2020).

Some of the current challenges hindering robotics growth in the construction industry are the complex job sites needed to be navigated by robots, autonomy needed to collect data, and general lack of connectivity on a construction site (Boston Dynamics, 2023). Robots that are able to operate with flexible autonomy are solutions to these challenges and have begun transforming the construction industry.

3D Printing

One particular use case of robotics in the construction industry is for 3D printing. At a high-level, 3D printing in the building and construction industries is performed using two major techniques: (1) binder jetting and (2) material deposition method (MDM). Both techniques require input of a 3D BIM/CAD file which is then separated and sliced into 2D layers. These layers then are “printed” by the robot using building materials such as concrete or steel (Tay et al., 2017). With the plethora of projected benefits from the technology, 3D printing has been explosive in the construction industry. The 3D printing construction market was worth 1.42 billion USD in 2021 and is expected to reach 750.75 billion USD by 2031, growing at a CAGR of 87.3% (C & S, 2022). 3D printing in the construction industry can help contractors save a lot of time, reduce excess material consumption, and save money from human errors while performing construction activities. Key benefits are summarized below:

1. <u>Cost reduction:</u> Across the entire value chain within a construction project, 3D printing helps reduce costs. Typical machine operation can be expensive and laborious, both of which would be considerably reduced (cost and time/physical labor needed) with the utilization of 3D printing. Material cost also decreases since there is less material excess and the 3D printed filaments being sold in bulk as the technology matures (Tractus3D, 2020).

2. <u>Time saved:</u> 3D Printing allows contractors to manufacture components of buildings in a fraction of the time needed to coordinate and build in the traditional construction method. As the technology becomes more sophisticated, 3D printing is able to output structures that are more complex than those built by physical laborers. Additionally, 3D printing allows for rapid prototyping of designs prior to full scale construction. This allows for designers, engineers, and contractors to coordinate high risk designs prior to full scale development.

3. <u>Production on Demand:</u> Finally, as 3D printing technology continues to mature, the technology will enable true production on demand. With less time, labor, and costs needed to produce structures, 3D printing can churn out full scale structures with unprecedented speed. Companies like ICON are using this technology to address societal issues like the need for affordable housing in the United States (Weiss, 2023).

The largest barriers to entry for utilizing 3D printing technology are intensive capital costs, printing errors, and technical skills required to operate the technology effectively. Additionally, 3D printers for large scale projects like houses require a significant amount of space which can be nearly impossible to acquire near urban areas.

<u>Augmented Reality/Virtual Reality (AR/VR)</u>

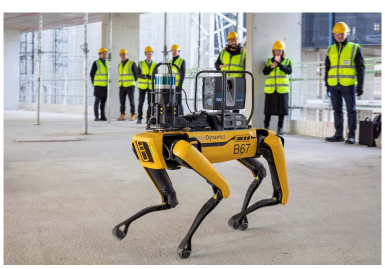
The final technology that JLL identifies as part of their construction technology hierarchy is Augmented and Virtual Reality. The terms Augmented Reality and Virtual Reality refer to a set of “technologies and experiences that bring computer-generated objects into the user’s physical environment” (Ellis, 2022a). The key difference between augmented reality and virtual reality technologies is the immersiveness of the experience the user feels when utilizing the technology and the setting in which the digital content is displayed. AR displays content in a real-world setting while VR generates an entirely new reality, typically through intensive hardware (Greenwald, 2021). With the AR industry expecting to see a 30%+ CAGR from 2022-2030, the market is positioned for exponential growth and is forecasted to amass a market value in 2030 of nearly 600 billion USD (Grandview Research, 2021). AR/VR technology can be utilized within the construction industry in a variety of ways:

1. Design Coordination: AR can enhance 3D models powered through BIM technology by simulating an even more realistic experience of the building design. Through virtual walk-throughs of buildings in progress, AR/VR technology enables stakeholders to catch coordination issues early on and also see the impact of proposed design modifications true to scale before issuing the go ahead (Biggs, 2020). This use case of AR/VR technology has the potential to save a lot of time and money associated with change orders and on-site clashing.

2. Safety Training: AR/VR technology can be leveraged for developing virtual tools to simulate safety scenarios that construction personnel need to be aware of and prepared for. Creating real world simulations is laborious and costly, whereas off-sourcing this to virtual environments ensures safe training conditions and ability to continue training anywhere.

3. Real-time Project Information: With AR/VR technology, field workers and on-site crews can have access to an enhanced view of all the design documentation of a project. Removing the need for contractors to flip back and forth between 2D plans/3D models and the physical site will inevitably save time and ensure minimal errors on site.

The major challenges associated with the widespread use of AR/VR technology in construction are the steep learning curve required for users, bandwidth needed on a job site for AR/VR to be used effectively, and the expense associated with purchasing the technology.

Secondary Impact Technologies - Early Development Stage		
Technology	**Description**	**Notable Companies**
Robotics 	The utilization of programmable autonomous objects in construction has helped with real-time project status documentation, increased safety on site, and environmental management on site.	Built Robotics Dusty Robotics Boston Dynamics Spot Scaled Robotics
3D Printing	3D printing technology has utilized advancement in robotics and materials science to develop a tool that prints 3D CAD project files through layered materials.	ICON Branch Technology

		
Augmented/Virtual Reality 	AR/VR technology brings computer-generated digital objects to the user's physical environment. This technology is typically powered by hardware such as headsets and software such as mobile applications (Ellis, 2022a).	Mira IrisVR AkularAR AR Instructor ARki

Table 13: Early Maturity Secondary Impact Construction Technologies Summary

Industry Interview: Brooke Gemmell

When evaluating these technologies for utilization and deployment in the field, it was helpful to get industry perspective. In an interview with Brooke Gemmell, Emerging Technology Project Manager at Skanska, I learned more about how professionals utilize these technologies on a daily basis on large scale commercial projects. Brooke first gave an overview of all the construction technologies that she has had experience with evaluating and implementing on her project sites, but noted that she has worked mostly with reality capture technologies such as drones, laser scanning, and matterport virtual tools. She believes that these technologies are most helpful for "filing claims, tracking renovations, or quickly validating on site conditions" and are relatively affordable to implement on site. On the other hand, Internet of Things (IoT) technology was referred to as "incredibly cost prohibitive at scale" and had less impact for site construction right now because of the infancy of the technology.

When asked how she selects construction technologies to pilot on a project site, Brooke described two major categorizations: 1) Push technologies are areas where the company would like increased attention into for research and development purposes whereas 2) Pull technologies are those that are being requested from site teams themselves. Brooke said she performed advantages analyses as designed in the lean six sigma methodology to help her prioritize technology implementation. Brooke listed 6 technologies when asked which technologies had the greatest impact on construction process efficiency: reality capture, data analysis tools, SitePrint robotics, Asset tagging, exo-skeletons, and AR for design verification. Her input on high impact and high value technologies aligned with other market reports like the JLL Construction Hierarchy previously described.

Finally, Brooke provided perspective on the development type and geographic application of these technologies. Specifically with regards to building affordable housing, Brooke asserted that "construction technology has the potential to unlock all aspects of the building process, from layout to close-out." She suggested that developers should consider implementing reality capture technologies for project progress and develop digital twins to streamline maintenance for end users since costs have to be kept low on affordable housing projects. In considering any geographic limitations on the types of technologies able to be utilized in the Pacific Northwest and Seattle, Brooke leaned on her experience working from the Portland office of Skanska USA. Other than keeping weather limitations top of mind and refraining from technologies like drones that are used in open air, Brooke highlighted the importance of understanding local trade and labor union requirements. She said that "unions want to ensure worker safety and privacy, which sometimes conflicts with tracking technologies such as wearables which are designed to monitor worker location."

Market Mapping

Through research and gleaning industry perspective, I designed a market map to help begin to prioritize technologies to recommend for affordable housing in Seattle. The two axes on the map below are maturity and impact (*Figure 13*). High maturity is defined as "a technology that has been in use for long enough that most of its initial faults and inherent problems have been removed or reduced by further development" ("Mature Technology," 2020). ✅On the other hand, high impact is a subjective designation that has been evaluated by my perspective following the research alongside the anticipated cost of implementing the technology. These inputs are listed below in *Table 14*.

Figure 13: Construction Technology Impact v. Maturity Market Map

			Impact vs. Maturity Inputs		
	Category	**Technology**	**Cost**	**Construction Market Size**	**Years in Market**
1	Foundational	BIM/CAD	low	$25B	20+
2	Foundational	Digital Twins	med	$17.5B	10+
3	Foundational	Artificial Intelligence	med	$8.6B	<5
4	Foundational	Digital Collaboration	low	$9.6B	20+
5	Primary Impact	Scanning	med	$1.4B	20+
6	Primary Impact	Drones	med	$4.5B	10+
7	Primary Impact	Modular Construction	high	$82.3B	20+
8	Secondary Impact - Incremental	Safety/Wearables	med	$4B	<5
9	Secondary Impact - Incremental	Financial	low	$2.1B	10+
10	Secondary Impact - Incremental	Equipment/Materials	low	$183.5B	20+
11	Secondary Impact - Incremental	Employment	low	$1.1B	10+
12	Secondary Impact - Early in Dev	3D Printing	high	$1.4B	<5
13	Secondary Impact - Early in Dev	Robotics	med-high	$129.7B	10+
14	Secondary Impact - Early in Dev	Augmented/Virtual Reality	med-high	$9B	<5

Sources: See Bibliography

Table 14: Impact vs. Maturity Inputs across 14 Construction Technologies

As also shown in Table 14, there are certain technologies that have a current (and projected) industry market size that greatly exceed that of peer technologies. For example, within the primary impact technology space, the market size for Modular Construction is valued at over 80 billion USD while the market size for scanning technologies is closer to 1.4 billion USD. This large variance can be explained by a variety of factors. For one, scanning technology can be patented by a small number of companies that then become the entire market, whereas modular construction *utilizes* technology but is more of a building process which is less able to restrict new players, and corresponding new innovation, to the sector.

Another aspect contributing to this large variance is the ambiguity associated with the industry itself. For example, isolating the value of drone technology specifically for use in the construction industry was difficult since the technology is now being utilized within a variety of industries. Finally, with areas such as construction equipment and material innovation, there are many ways to apply technology solutions to drive toward cheaper buildings that are also resilient and less complex to build. It was difficult to understand how much of the 183 billion USD market size could specifically be attributed to growth in the material and equipment marketplace sector, and therefore added some challenges to this methodologies.

Technology Utilization

Many of the technologies described above are utilized throughout the lifespan of a construction project. *Table 15* below maps the technologies to their most frequently used deployment location on a project site. The locations listed are those categorized previously within the McKinsey study: back-office, on-site, and on digital platforms. Understanding where technologies are most likely utilized is helpful in filtering technologies during the application component of this thesis.

Category	Technology	Deployment Location Back-Office	 Digital Collaboration	 On-Site
Foundational	BIM/CAD	x	x	x
Foundational	Digital Twins	x	x	
Foundational	Artificial Intelligence		x	x
Foundational	Digital Collaboration	x	x	x
Primary Impact	Scanning			x
Primary Impact	Drones			x
Primary Impact	Modular Construction			x
Secondary Impact - Incremental	Safety/Wearables	x		x
Secondary Impact - Incremental	Financial	x		
Secondary Impact - Incremental	Equipment/Materials		x	x
Secondary Impact - Incremental	Employment	x		
Secondary Impact - Early in Dev	3D Printing			x
Secondary Impact - Early in Dev	Robotics	x	x	x
Secondary Impact - Early in Dev	Augmented/Virtual Reality	x	x	x

Table 15: Deployment Location across 14 Construction Technologies

Construction Technology Summary

The construction industry has seen a significant level of modernization over the last 30 years. Through integration of modern technologies such as digital coordination, robotic processing, and highly accurate visualization and location tracking, the field of construction technology has become populated with significant opportunities for expansion. During this section of the thesis, I utilized a few key industry reports in order to narrow and prioritize 14 major areas of construction technology innovation. Alongside literature reviews, industry research, and a few conversations with professionals, I developed an industry map to document high opportunity areas. Technologies that fell under high perceived impact and maturity are those that I believe have the greatest potential overall to drive significant efficiency in the construction industry overall. In Section 6, I will prioritize and apply these technologies specifically within the contexts of affordable housing development in the Seattle, WA area.

Section 6: Application and Opportunity

In order to better understand how the construction technologies described in Section 5 can be applied to increase the supply of affordable housing in Seattle, I have taken the following analysis approach:

1. Obtain the average development cost of an affordable housing unit in Seattle.
2. Determine the fraction of the total development cost that can be attributed to construction costs.
3. Break down the cost per construction activity to understand where cost is incurred on site.
4. Isolate which activities/trades have the greatest potential for cost reduction through implementation of construction technology.
5. Determine which construction technologies would most advance work contained within the trade scopes.
6. Develop a recommendation of technologies the City of Seattle can pursue in order to make the affordable housing development process more efficient and yield more units.

Analysis

#1: Obtain the average development cost of an affordable housing unit in Seattle.

In a report to the Washington State Legislature in December 2020, the Washington State Housing Finance Commission (WSHFC) analyzed the costs of developing low-income housing (Washington State Housing Finance Commission, 2020). These costs were collected as a requirement of the federal Low-Income Housing Tax Credit (LIHTC) program, where developers are unable to redeem housing tax credits from the IRS until costs have been verified to meet LIHTC thresholds. Total Residential Project Cost refers to a summation of all costs including land, capitalized reserves, and infrastructure costs associated with the residential budget. For King County in 2020, the average cost per affordable unit was $315,046 with an average cost per residential square foot of $364.

#2: Determine the fraction of the total development cost that can be attributed to construction costs.

When analyzing average unit cost, the WSHFC broke down costs into the major categories depicted in *Figure 14* below. These cost areas are defined in *Table 16*.

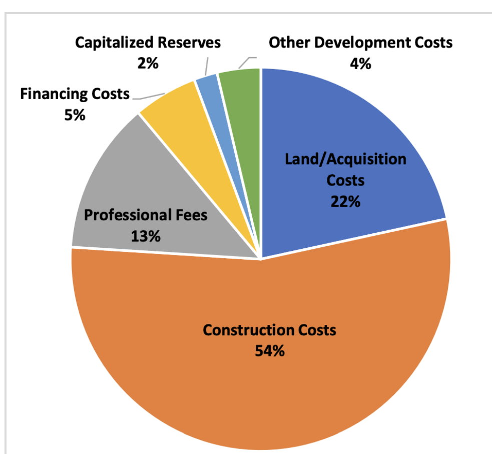


Figure 14: Residential Project Costs Breakdown (Source: Washington State Housing Finance Commission)

Category	Definition
Land/Acquisition Costs	Cost for acquiring land, buildings, and any closing costs
Construction Subtotal	Materials, labor, and associated costs of residential construction; any site or infrastructure work; and contingency
Professional Fees	Engineering, architecture, appraisals, market studies, Geotech, topograph, environmental reports, legal fees, development consultant, developer fees
Financing Costs Subtotal	Loan fees, interest expenses, and insurance
Capitalized Reserves Subtotal	Operating and/or replacement reserves
Other Development Costs Subtotal	Real estate tax, insurance, relocation, bidding costs, permits/fees/hookups, impact mitigation fees, development period utilities, nonprofit donation, accounting audit, marketing leasing expenses, and any carrying costs at rent up reserve

Table 16: Residential Project Costs Category Definitions (Source: Washington State Housing Finance Commission)

To determine the average cost spent on construction activities for affordable housing units in Seattle, I applied the percentages provided by the Washington State Housing Finance Commission to the total development cost. As seen in *Table 17* below, the amount spent on construction activities is 54% of $315,046, which is approximately $170,125.

Costs (by percentage)		
Construction (per Unit)	**54%**	**$ 170,124.84**
Financing	5%	$ 15,752.30
Professional Fees	13%	$ 40,955.98
Land/Acquisition Costs	22%	$ 69,310.12
Capitalized Reserves	2%	$ 6,300.92
Other Development Costs	4%	$ 12,601.84
	100%	$ 315,046.00

Table 17: Extracted Cost Categories for Affordable Housing Unit Development in Seattle

#3: Break down the cost per construction activity to understand where cost is incurred on site.

The National Association of Home Builders' (NAHB) Construction Cost Survey is a grounding document to understand how costs are distributed within the construction phase of developing a home (Lynch, 2023). An important caveat of the NAHB survey for this analysis is that it provides a national average of single-family home construction, whereas most affordable housing units are built within multi-family units. This will be discussed in further detail below. *Table 18* below records the result of the 2022 NAHB Construction Cost Survey and applies the percentage allocations (share %) to affordable housing in Seattle. As seen in the final line item of the table, the allocations are pulled back from the approximate construction phase costs determined above of $170,125.

Single Family Home Construction	*Source: NAHB, Construction Cost Survey*				
		Average in US	**Share (%)**		**Applied to Seattle Affordable Housing**
Site Work	**$**	**29,193**	**7.4%**	**$**	**12,661.77**
Building Permit Fees	$	8,292	2.1%	$	3,596.46
Impact Fee	$	5,208	1.3%	$	2,258.85
Water & Sewer Inspection Fees	$	5,800	1.5%	$	2,515.61
Architecture, Engineering	$	4,724	1.2%	$	2,048.92
Other	$	5,169	1.3%	$	2,241.93
Foundations	**$**	**43,086**	**11.0%**	**$**	**18,687.54**
Excavation, Foundation, Concrete, Retaining walls, and Backfill	$	39,731	10.1%	$	17,232.38
Other	$	3,355	0.9%	$	1,455.15
Framing	**$**	**80,280**	**20.5%**	**$**	**34,819.55**
Framing (including roof)	$	60,831	15.5%	$	26,384.01
Trusses (if not included above)	$	11,479	2.9%	$	4,978.75
Sheathing (if not included above)	$	5,383	1.4%	$	2,334.75
General Metal, Steel	$	1,161	0.3%	$	503.56
Other	$	1,419	0.4%	$	615.46
Exterior Finishes	**$**	**46,108**	**11.8%**	**$**	**19,998.26**
Exterior Wall Finish	$	19,746	5.0%	$	8,564.36
Roofing	$	11,496	2.9%	$	4,986.12
Windows and Doors	$	13,158	3.4%	$	5,706.97
Other	$	1,709	0.4%	$	741.24
Major Systems Rough-ins	**$**	**70,149**	**17.9%**	**$**	**30,425.47**
Plumbing	$	22,706	5.8%	$	9,848.19
Electrical	$	23,892	6.1%	$	10,362.59
HVAC	$	21,845	5.6%	$	9,474.75
Other	$	1,707	0.4%	$	740.37
Interior Finishes	**$**	**94,300**	**24.0%**	**$**	**40,900.40**
Insulation	$	6,530	1.7%	$	2,832.23
Drywall	$	13,184	3.4%	$	5,718.25
Interior Trims, Doors, and Mirrors	$	12,727	3.2%	$	5,520.04
Painting	$	8,793	2.2%	$	3,813.76
Lighting	$	4,502	1.1%	$	1,952.64
Cabinets, Countertops	$	17,775	4.5%	$	7,709.49
Appliances	*$*	*6,263*	1.6%	$	2,716.43
Flooring	$	13,019	3.3%	$	5,646.68
Plumbing Fixtures	$	5,166	1.3%	$	2,240.63
Fireplace	$	1,608	0.4%	$	697.43
Other	$	4,733	1.2%	$	2,052.83
Final Steps	**$**	**23,065**	**5.9%**	**$**	**10,003.90**
Landscaping	$	9,123	2.3%	$	3,956.89
Outdoor Structures	$	2,178	0.6%	$	944.66
Driveway	$	8,775	2.2%	$	3,805.95
Cleanup	$	2,280	0.6%	$	988.90
Other	$	709	0.2%	$	307.51
Other	**$**	**6,059**	**1.5%**	**$**	**2,627.95**
Total Construction Cost	**$**	**392,240**		**$**	**170,125**

Table 18: Construction Activity Costs for Single-Family Housing (Source: NAHB)

#4: Isolate which activities/trades have the greatest potential for cost reduction through implementation of construction technology.

In order to recommend construction technologies that would uniquely improve construction efficiency for housing development, it was important to understand where the majority of cost is spent on site. Utilizing the NAHB Construction Cost Survey data, the percentage breakdown of primary construction activities is displayed in *Figure 15* below. It is important to note that the cost breakdown utilized refers to traditional construction methods and does not take into account the breakdown of trade area costs incurred when leveraging modular or factory construction practices.

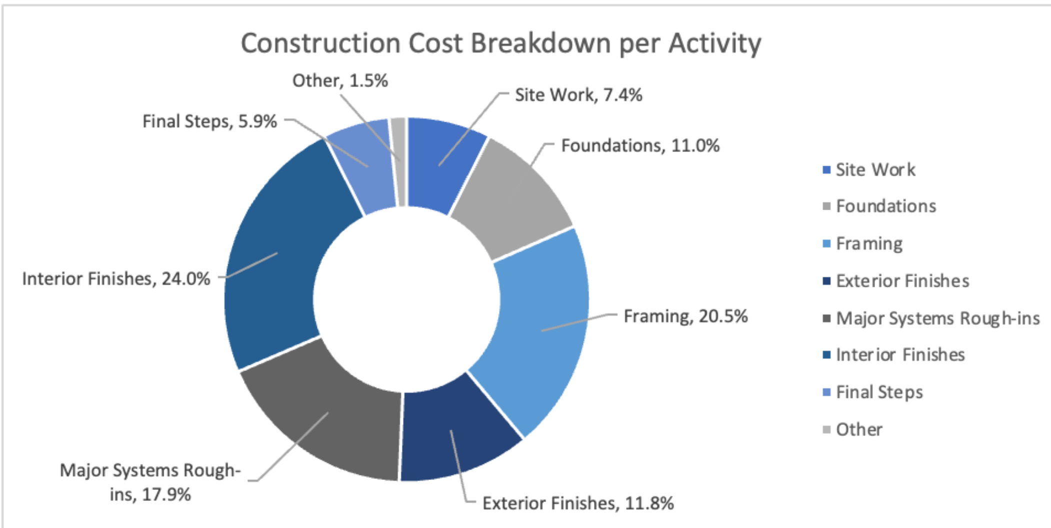


Figure 15: Construction Cost Breakdown per Activity

The three major areas where work is completed on site for housing development are Interior Finishes (24%), Framing (20.5%), and Major Systems Rough-Ins (17.9%). Integrating technologies that target these three cost categories are likely to offset the most costs (62.4%) associated with the construction phase of the development project. Interior finishes describe work such as painting, drywall, adding insulation, and flooring and is considered to be both highly variable in scope, requires time, as well as requires skilled labor and craftsmanship. Framing activities require an advanced degree of precision and are also quite laborious, although it is fairly repetitive throughout a project. Finally, activities within the major system rough-ins work include integrating the plumbing, electrical, and mechanical systems within the property structure. These trades require a lot of coordination between technical subcontractors and a significant amount of labor to set up.

#5 Determine which construction technologies would most advance work contained within the trade scopes.

Filtering *Table 15* above for technologies deployed on-site is the first step in determining which technologies would have a significant impact in decreasing costs on site. The next step is to understand where technologies are used during the construction process. The right hand (blue) side of *Table 19* below notes the trade areas that typically have tasks that correspond with functionalities of the on-site construction technologies. For example, BIM/CAD technologies have been used across the entire construction phase of a development project and contribute to increased efficiency for trades from site work to interior framing. On the other hand, there is more limited utilization for drones on site. Since this technology mostly targets obtaining aerial footage of progress on site, it is commonly deployed during the site work and foundation setting stage.

			Deployment Location			***Trade Area Utilization***						
	Category	**Technology**	**Back-Office**	**Digital Collaboration**	**On-Site**	**Site Work**	**Foundations**	**Framing**	**Exterior Finishes**	**Major Systems Rough-Ins**	**Interior Finishes**	**Final Steps**
1	Foundational	BIM/CAD	x	x	x	x	x	x	x	x	x	x
3	Foundational	Artificial Intelligence		x	x	x	x		x	x		
4	Foundational	Digital Collaboration	x	x	x	x	x	x	x	x	x	x
5	Primary Impact	Scanning			x	x	x	x				
6	Primary Impact	Drones			x	x	x		x			x
7	Primary Impact	Modular Construction			x		x	x	x	x	x	
8	Secondary Impact - Incremental	Safety/Wearables	x		x	x	x	x	x	x	x	x
10	Secondary Impact - Incremental	Equipment/Materials		x	x	x	x	x	x	x	x	x
12	Secondary Impact - Early in Dev	3D Printing			x		x	x		x		
13	Secondary Impact - Early in Dev	Robotics	x	x	x	x	x	x	x	x	x	
14	Secondary Impact - Early in Dev	Augmented/Virtual Reality	x	x	x	x	x	x	x	x	x	x

Table 19: Technologies Utilized On-Site Across Various Trade Areas

We can then begin to distill the original list of 14 technologies to a handful that are likely to have the greatest impact within the three trade areas that were found to be the greatest contributors to overall residential construction costs. The on-site technologies believed to be utilized within these work areas are listed below in *Table 20*.

Interior Finishes	**Major System Rough-Ins**	**Framing**
BIM/CAD	BIM/CAD	BIM/CAD
Digital Collaboration	Artificial Intelligence	Digital Collaboration
Modular Construction	Digital Collaboration	Scanning
Safety/Wearables	Modular Construction	Modular Construction
Equipment/Materials	Safety/Wearables	Safety/Wearables
Robotics	Equipment/Materials	Equipment/Materials
Augmented/Virtual Reality	3D Printing	3D Printing
	Robotics	Robotics
	Augmented/Virtual Reality	Augmented/Virtual Reality

Table 20: Technologies Utilized On-Site for Framing, Rough-Ins, and Interior Finishes

#6 Develop a recommendation of technologies the City of Seattle can pursue in order to make the affordable housing development process more efficient and yield more units.

The final stage of this analysis is to develop a recommendation of technologies that will uniquely help developers in the City of Seattle be able to create more affordable housing stock. Cross-referencing the market map developed in *Table 13* and focusing on the upper left hand quadrant of technologies that have <u>both</u> the greatest perceived impact and are the most developed (and therefore ready to utilized/vetted), we can filter the original list of 14 construction technology areas to focus on 6. These technologies span across foundational, primary, and secondary technology categories and are also innovations that have potential to create efficiencies in the targeted high-cost trade areas above of Interior Finishes, Framing, and Major System Rough-Ins. These six technologies are summarized in *Table 21* below and recommended alongside potential providers as well as anticipated cost saving areas from deployment on site.

Hierarchy Category	Technology	Potential Provider	Anticipated Cost Saving Areas
Foundational	BIM/CAD	Autodesk Revit	Time and Labor saved from modifications to the designs.
	Digital Collaboration Tools	BIM 360	Time (Labor) saved from unnecessary rework, miscommunication due to outdated plans.
Primary	Scanning	Matterport	Real time data capture can surface design coordination issues.
	Modular Construction	Blokable	Labor savings from coordinating multiple trade work, quality control costs diverted.
Secondary	Robotics	HP SitePrint	Time + Money Saved from physical layout on site.
	Augmented/Virtual Reality	Mira Reality	Labor hours saved from training on site, time saved from enhanced 3D coordination.

Table 21: Recommended Technologies Summary

Projecting Cost Savings

Anticipating and calculating cost savings from the utilization of construction technology is a difficult process. On one hand, there's quantifying the immediate benefits that are realized when a technology saves time or decreases labor hours required. On the other hand, there are anticipated cost savings from avoiding safety incidents, rework, and other negative behaviors that often occur on site as a result of poor planning and lack of coordination. Finally, there are the costs associated with the technology itself (equipment, personnel/training required) and how capital costs are spread over time (depreciation rate) and across projects (shelf life). There are a variety of studies that have tracked these cost savings over a multitude of projects and have estimated the percentage of total work cost that was saved through utilizing technologies.

The most accurate approach to understanding the true impact of implementation of these technologies on the overall cost of a project is to establish a "control" project and then utilize technologies on similar projects one by one to compare cost outcomes. For example, if developers were able to select a handful of technologies to introduce to a series of residential affordable housing projects during the same year and with similar scopes (size, contractors, etc), they would really be able to isolate the true effect of the technology accounting for the geographic conditions unique to development in Seattle. However, for the scope of this thesis and not having access to that information, I decided to pursue another general approach. *Table 22* below shows cost savings possibilities per trade area by leveraging industry-sourced cost savings percentages. For example, it is estimated that Digital Collaboration tools have a total project savings of 5% so I applied that percentage to the costs of the interior finishes, framing, and system rough-ins trade areas to project a potential cost savings/unit through implementation of the technology (Koeleman, João Ribeirinho, Rockhill, Sjödin, & Strube, 2019).

Average Cost per Affordable Housing unit in Seattle	**$ 315,046.00**
% allocated to Construction Costs	**54%**
Construction Costs	**$ 170,124.84**

	% allocation	*$ contribution*
Interior Finishes	24.00%	$ 40,829.96
Framing	20.50%	$ 34,875.59
MEP Rough-Ins	17.90%	$ 30,452.35

Technology	**% cost savings**	*Interior Finishes*	*Framing*	*MEP Rough-Ins*	**Potential Cost Savings/unit**
BIM/CAD	20%	$ 1,959.84	$ 1,429.90	$ 1,090.19	$ 4,479.93
Digital Collaboration Tools	5%	$ 489.96	$ 357.47	$ 272.55	$ 1,119.98
Scanning	3%	$ 293.98	$ 214.48	$ 163.53	$ 671.99
Modular Construction	25%	$ 2,449.80	$ 1,787.37	$ 1,362.74	$ 5,599.91
Robotics	13%	$ 1,273.89	$ 929.43	$ 708.63	$ 2,911.96
Augmented/Virtual Reality	10%	$ 979.92	$ 714.95	$ 545.10	$ 2,239.97

Sources:
https://plannerly.com/how-bim-helps-in-reducing-the-cost-of-construction/
https://www.mckinsey.com/capabilities/operations/our-insights/decoding-digital-transformation-in-construction
https://www.geoweeknews.com/news/cost-justification-of-laser-scanning
https://constructiondigital.com/construction-projects/modular-construction-rising-10-reasons-why
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9244236/

Table 22: Projected Cost Savings for 6 key technologies

A major assumption that is made during this calculation process is that the cost savings from utilizing these technologies are equal across trades, which is likely not true in practice. For example, while modular construction processes can be utilized across all three trade areas, the impact of the technology may be felt more strongly in more technically complicated scopes like interior finishes or MEP systems. These trade areas require a lot of different materials, application techniques, and on-site assembly coordination between many subcontractors. The labor costs and time associated with this work are high - therefore making these trade areas prime candidates for embedding modular construction technology. On the other hand, framing is laborious and time consuming but doesn’t require as much multi-scope coordination so it is anticipated that it wouldn’t realize as much efficiency gains as the other trade areas.

Prioritizing Technology Deployment

Beyond just projections of cost savings per technology, an important consideration when deciding which technologies to invest in the development process is the phasing of technologies. Since many of these technologies augment the efficiency of other technologies, combining or phasing them in intentional ways can reduce costs on site. Additionally, if there is a limited budget (which there often tends to be in affordable housing development), it makes more sense to recommend foundational technologies first before jumping to more sophisticated and capital cost intensive technologies. *Figure 16* below shows the recommended technology phasing for the 6 technologies distilled previously.

Since BIM/CAD and Digital Collaboration Tools enable the backbone of many other construction technologies, I believe that these are critical starting points for any development project. These two foundational technologies help power modular construction, scanning, and AR/VR spaces to be integrated into the next phase of technologies. Since AR/VR tools and Scanning both require relatively small and mobile equipment, I would recommend prioritizing those technologies before Modular Construction. Finally, if there was capacity for additional technology integration, I would introduce robotics and modular construction onsite to enable greater efficiencies and dramatically reduce time spent performing certain activities.

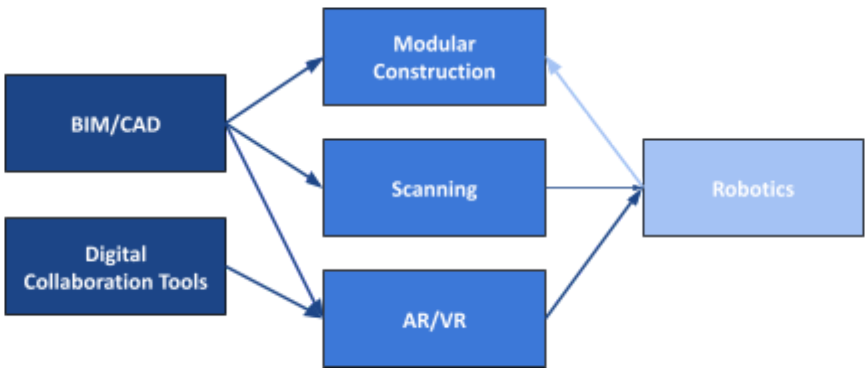


Figure 16: Recommended Technology Phasing

Economies of Scale

These costs are currently estimated as savings per affordable housing unit. However, most affordable housing units are built in the form of apartments within low/med/high rise multifamily complexes rather than in a single-family dwelling. A majority of both the market rate and affordable housing units coming up in Seattle are also in the form of mixed-use and multiplex dwellings. This is because scale introduces a much greater opportunity for saving costs. As shown in *Figure 17* below, even though new construction is expensive, density can create more affordable options (DiRaimo, 2021). When a land parcel is utilized to house more people, the land acquisition costs are spread over each unit and reduce the individual unit cost. While historically costs increase linearly with the number of units that are designed, these costs can become less significant through utilizing technologies that offset the additional developer and contractor costs.

Utilizing construction technologies during the building process of these affordable housing units would further the value of the funding that is being provided on a local and federal level significantly. Many affordable housing developments are designed as repeatable design units which have the potential to greatly benefit from robotics and modular construction technologies that specialize in producing identical components. Technologies with high capital cost inputs like robotics, modular construction, and

AR/VR are cost inefficient when utilized for a handful of projects but the investments pay off when the scale of projects and units produced increases. This economic theory of high costs being spread over a large number of outputs is called economies of scale.

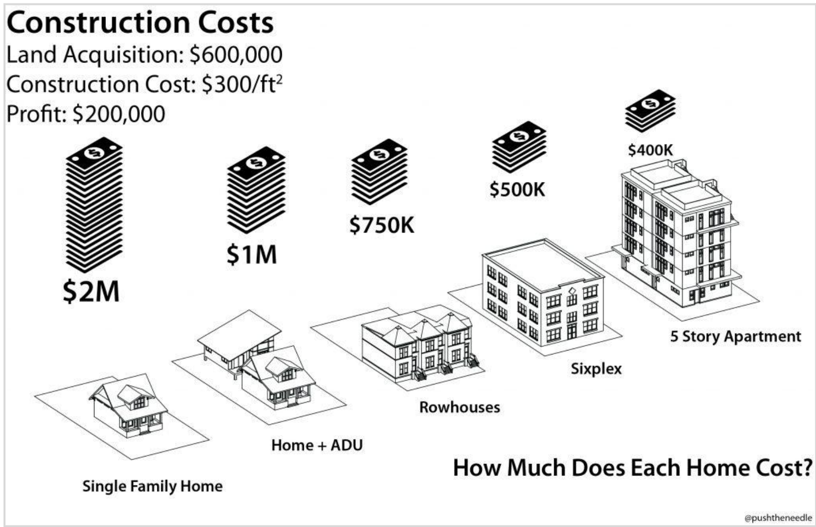


Figure 17: Construction Costs Distributed by Housing Typology (Source: the Urbanist)

When economies of scale are truly achieved, builders would understand the right technologies to utilize in building each typology of affordable housing. This means that by implementing certain construction technologies, builders are able to lower the average unit development cost (by reducing construction costs) to a level that is low enough to encourage continued output. When unit costs are lower, developers do not have as high of a barrier to entry to engage with housing projects and are incentivized to build more.

Opportunity Areas

There are a variety of ways to distill and recommend which construction technologies the City of Seattle should utilize in stretching the limited funding available for affordable housing. In future analyses, I would like to focus additional research efforts on understanding the effectiveness of utilizing a handful of technologies such as modular construction and projecting their impact on a variety of housing typologies. I am particularly interested in understanding how robotics technologies are able to reduce both operating and capital costs throughout the stages of construction and across all trade areas. Additionally, I would be extremely interested in reviewing the components of the cost that are attributed across the labor and material categories. Implementing technologies that assist with labor utilization would be another criteria addition to overall savings metrics. Finally, as mentioned earlier, a lot of cost savings from technology utilization stems from the avoidance of safety incidents and rework on site. Quantifying how often those behaviors occur on-site and then finding research to develop a clear technology strategy to eliminate these unforeseen costs would be very important to understand.

Conclusion

This thesis had two major goals: 1) set out to understand how existing technologies currently advance the design, construction, and scalability of affordable housing and 2) to recommend technology for affordable housing development in Seattle, WA. I approached this research by developing a strong foundation of geographic context, inventorying the current landscape of construction technology innovations, and analyzing these technologies to develop a recommendation for which to prioritize in Seattle.

It is clear that both the United States and the city of Seattle are experiencing issues with a lack of available and affordable housing stock. This issue is particularly difficult for low income communities and communities of color. While the city has been growing and has added nearly 60,000 housing units to market since 2015, these units are still largely out of reach to lower income households. A predominant reason for why units are being listed and rented at higher costs is because the unit cost of developing any housing in Seattle is significantly higher than across the country. Increasing unit supply for these households is critical to meet the City's goal of ensuring that "all people have access to housing that is safe, clean, and affordable."

In this thesis, I have focused on understanding where costs are incurred in affordable housing development and have investigated solutions that target the 1) reduction of construction costs (54% of total development costs), and 2) the reduction of costs within the most expensive construction trades on a residential project. It is important to note that some of the technologies recommended are early in development and cost savings are still very much under close monitoring from ongoing projects. Through analysis, it was determined that in order to offset some of the costs associated with the most expensive trade areas of Interior Finishes, Framing, and Rough-Ins, technologies such as BIM/CAD and scanning would be beneficial to implement right away. Other technologies identified that are more cost prohibitive but likely would yield significant savings are modular construction, AR/VR, and robotics.

For these technologies to mature, investment from key stakeholders will be imperative. Buy-in will enable widespread availability and utilization, ultimately leading to more sophisticated technology and lower barriers to entry. It will be necessary to engage with key stakeholders within the development process to re-envision how their workflows will adapt to emerging technologies:

- General Contractors (GC): GCs will need to evolve their current training processes to incorporate construction technologies into their workflow. Additionally, GCs will need to restructure their financial expenditures and prepare to make larger upfront investments.
- Architects & Engineers: With technologies transforming workflows and project design capabilities, Architects and Engineers will need to modify design standards to account for innovation.
- Real Estate Developers: Real estate developers will need to pursue projects designed and built with construction technology. Striving for economies of scale will drive technology adoption and increase affordable housing stock.

- Policymakers: Policymakers will need to continue to advocate for bills reshaping zoning to accommodate a diversity of housing densities (mid, low, high) and forms (sizes, locations), as suggested by Phillips in *The Affordable City*.
- Planners: Zoning still remains a major barrier to freeing up development capacity for affordable housing. Using Artificial Intelligence technology has been an important tool in scenario planning. Additionally, leveraging construction technology to expedite permitting and automate code compliance checks would aid the planning department in processing more development projects.

It is imperative that the industry and its key players embrace the adoption of construction technology into our standard development processes. These technologies are positioned to be game-changing in driving the efficiency needed to keep up with demand for affordable housing. Through increased collaboration, real-time progress tracking, building efficiencies, and reduced labor hours required to develop housing units, we will be able to build more at the pace we need. Housing is a basic human right, and by leveraging the right resources and by supporting innovation, our industry can provide for all of our communities.

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Appendix

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Acronyms:

ACS	American Community Survey Data
AEC	Architecture, Engineering, and Construction Industry
AI	Artificial Intelligence
AR	Augmented Reality
BIM	Building Information Modeling
CAD	Computer Aided Design
CAGR	Compound Annual Growth Rate
CHAS	Comprehensive Housing Affordability Strategy
CSG	Constructive Solid Geometry
DPD	City of Seattle Department of Planning and Development
FAR	Floor Area Ratio
GC	General Contractor
GMA	Growth Management Act (State of Washington)
HDS	High Definition Surveying
HUD	US Department of Housing and Development
MDM	Material Deposition Method
MEP	Mechanical, Electrical, and Plumbing Trades
ML	Machine Learning
NAHB	National Association of Home Builders
OFM	Office of Financial Management (State of Washington)
OPCD	City of Seattle Office of Planning and Community Development
VR	Virtual Reality

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