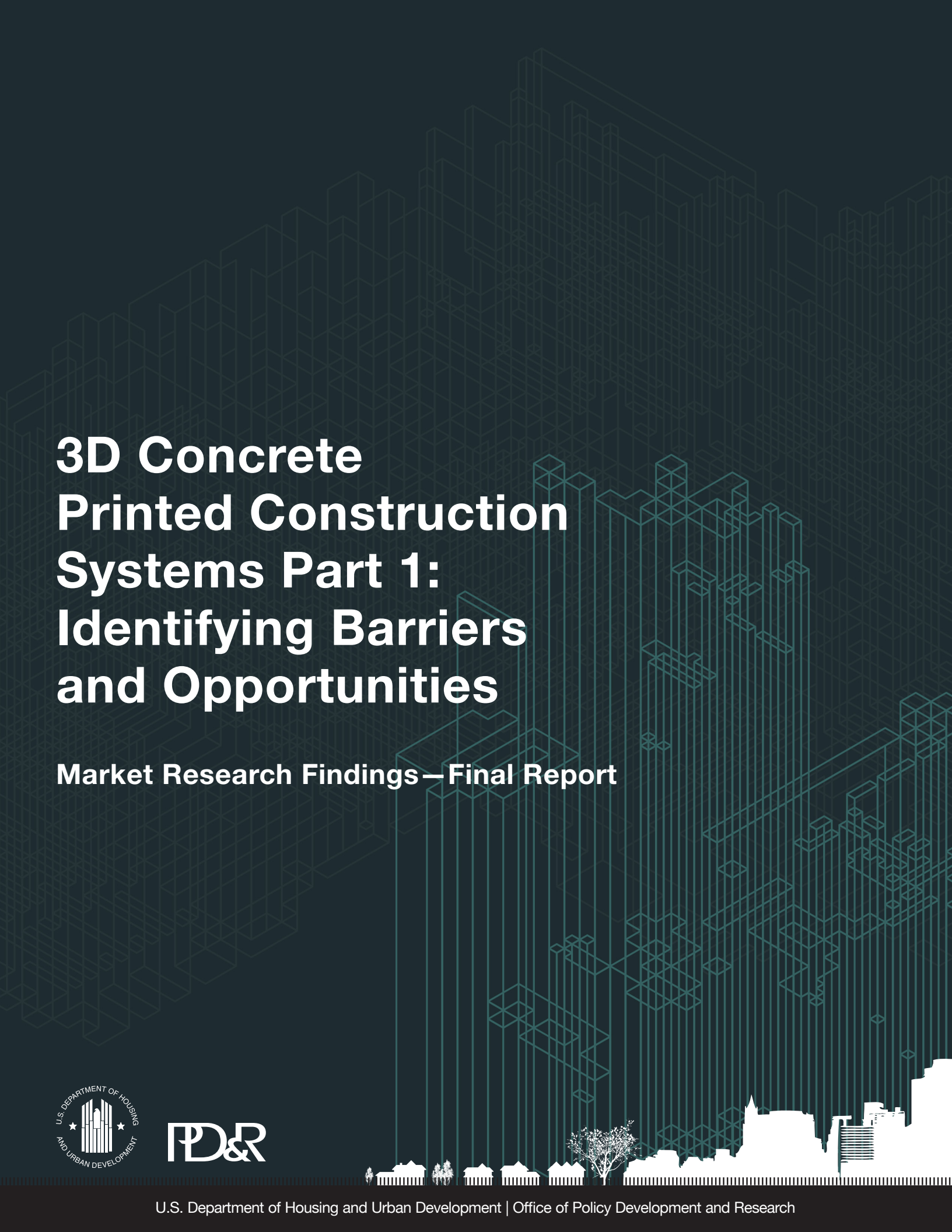
3D Concrete Printed Construction Systems Part 1: Identifying Barriers and Opportunities

Market Research Findings—Final Report



U.S. Department of Housing and Urban Development | Office of Policy Development and Research

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3D CONCRETE PRINTED CONSTRUCTION SYSTEMS PART 1: IDENTIFYING BARRIERS AND OPPORTUNITIES

MARKET RESEARCH FINDINGS—FINAL REPORT

Prepared for

U.S. Department of Housing and Urban Development
Office of Policy Development and Research

Prepared by

Home Innovation Research Labs

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Foreword

HUD has studied the diffusion of innovation in the residential building industry for decades. HUD has also encouraged innovative solutions to improve the affordability and performance of housing, with a special emphasis on low- and moderate-income families. Innovative solutions are needed to address today's housing challenges, which include a shortage of affordable housing supply, the need for resilient construction to reduce damage by natural disasters, and housing solutions for people experiencing homelessness and other at-risk populations.

Three-dimensional concrete printing (3DCP) technology is an innovative method of construction, using robotics and specially formulated concrete material to achieve greater design flexibility, faster material hardening times, and a wide range of mechanical properties without the need for conventional formwork. The technology has been in development for years in various universities, but adoption has been slow in the United States.

3DCP residential buildings have the potential to address many housing supply challenges, including the current labor shortages in the construction industry. In addition, 3DCP residential buildings are concrete structures that can resist natural hazards, such as high wind conditions and fire, so 3DCP technologies could improve resilience. In the past few years, many types of residential buildings have been constructed using 3DCP technology, from single-family homes to larger apartment buildings.

This research study, conducted for HUD's Office of Policy Development and Research by the Home Innovation Research Lab, draws on interviews of home builders and contractors, visits to job sites, and a national survey of 305 homebuilders to understand challenges and opportunities in accelerating the adoption of 3DCP technology in residential buildings.

The two-part primer provides (1) an overview of the market potential for 3DCP technology and (2) an introduction to 3DCP construction practices. The research highlights consideration for builders, developers, architects, and design professionals in the context of designing buildings with 3DCP technology, contributing to a better understanding of the challenges and opportunities in the adoption of innovative construction methods.

Solomon Greene
Principal Deputy Assistant Secretary for Policy Development and Research
U.S. Department of Housing and Urban Development

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Executive Summary

The marketing research portion of this study aimed to uncover market barriers and opportunities to the widespread adoption of three-dimensional concrete printing (3DCP) construction technology. Once identified, specific barriers and opportunities can be addressed through both technology enhancements and adjustments and marketing strategy refinements to increase the likelihood of a successful market introduction. This study looks deeply into the views and experiences of home builders and specialty contractors—decisionmakers known to strongly influence the adoption of new construction materials and process technologies.

The first phase of this research was a qualitative assessment of construction decisionmakers. Home Innovation Research Labs held a series of in-person interviews with builders and contractors at a 3DCP jobsite in Austin, Texas, followed by videoconference interviews with construction professionals throughout the nation. These interviews were designed to discover barriers to 3DCP adoption early in the life of the technology. Furthermore, although many who offer this technology target above-grade walls, this study sought deeper insights to discover less obvious opportunities in which unmet needs exist in a wide variety of applications (floors, roofs, foundations, and so on) and construction types (single-family, multifamily, nonresidential, and so on). The report, "Exploratory Research: Construction Considerations With 3D Concrete Printed Walls," issued findings in October 2021 from the first phase of research.

The next phase of research, detailed in this report, was a national survey of home builders fielded among a sample of 305 during August 26th through the 30th, 2022. The purpose of the survey research was to validate market opportunities for 3DCP technology and understand barriers that currently exist to its widespread adoption, including elements that design details and product refinements needed to address.

The findings of the national survey suggest that general awareness of 3DCP is fairly high—about three-fourths of respondents knew of this technology—but only one-fourth of those with awareness had investigated it, and only 1 percent reported using it on construction projects.

Survey participants were asked to review a video of 3DCP technology and read a detailed description prior to answering opinion-related questions on the topic. About one-third of the survey participants believed they were likely to adopt 3DCP in the future, although most of the remainder had no opinion (38 percent) or said they were unlikely to adopt it (nearly 30 percent). Willingness to adopt it based on size or type of builder and geographic region differed.

- Regional and national builders reported they were more likely to adopt 3DCP technology than builders operating in only one market area.
- Multifamily builders and those currently constructing homes with concrete above-grade walls were much more likely than average to express a willingness to adopt it.
- Builders who lead their market in cost-reducing innovation were more willing to adopt 3DCP technology than were market leaders in home quality or energy performance.
- Builders in the hottest climates (International Energy Conservation Code zones 1 and 2) were most receptive to adopting this technology.

The biggest advantages of 3DCP technology over existing construction methods as respondents reported were increased construction speed, labor savings, simplification of the construction

process, increased durability, and disaster resistance. Of these benefits, respondents said labor and cost reductions were the most important.

When asked about the perceived negatives of 3DCP and barriers to adopting it, builders said they believe construction costs likely would be higher than their current practice. Some also believe the learning curve will be very steep for their subcontractors—particularly the steps related to routing utilities in walls. They expressed concerns about the problems that would be created as a result of correcting mistakes in routing utilities after the concrete cures. Also, some reported that they expect a lack of demand among homebuyers for homes constructed using 3DCP technology.

Participants were also asked to evaluate opportunities that may speed up the adoption of 3DCP technology. Builders indicated they are more likely to adopt the new technology if interior and exterior finish surfaces are offered in a variety of textures (not just ribbon). Another important factor is for 3DCP suppliers to offer the capability to print foundation and above-grade walls in a single printing. Builders saw 3DCP's greatest potential for use in simpler construction types, such as privacy and retaining walls, foundations, utility structures (for example, garages and outbuildings), and affordable housing. They saw the least opportunity in luxury homes.

Home builder respondents had several objections to the technology that would need to be overcome for them to consider adopting 3DCP technology. They must be assured that (1) the technology will readily meet building codes, (2) availability of equipment and material will be widespread, and (3) strength and performance will be guaranteed.

The survey findings suggest that 3DCP construction technology has significant potential to make inroads into residential construction. To accomplish this goal, 3DCP suppliers should strategically target the most receptive technology adopters, as defined in this study, and continue to refine and enhance the technology in response to market feedback. The best way for 3DCP suppliers to inform the industry of this technology is through in-person demonstrations hosted by manufacturers, suppliers, or contractors.

Introduction

This research project investigates three-dimensional concrete printing (3DCP) technology by exploring two key construction issues. First, this authoring team identifies barriers to adopting 3DCP technology such as the lack of building codes or standards, design and construction guidance, and technical expertise to implement the new technology. Second, the team describes typical construction practices needed to integrate 3DCP technology into conventional construction by evaluating how 3DCP walls are installed with conventional building product components.

Two reports present the research findings. *Part 1: Identifying Barriers and Opportunities* summarizes the qualitative market research results based on focus groups and surveys with home builders and contractors. The team explores the challenges and opportunities to accelerate adopting 3DCP technology. *Part 2: An Overview of 3DCP Construction Practices* provides builders, contractors, and developers with information about installing 3DCP technology.

Home Innovation Research Labs (Home Innovation) fielded a national survey of home builders from August 26 to 30, 2022, to validate market opportunities for 3D Concrete Printing (3DCP) technology and to understand barriers that currently exist to its widespread adoption. This work follows an earlier qualitative research phase in which Home Innovation's marketing research team interviewed construction contractors at a jobsite in Austin, Texas, during construction of a 3DCP home. Videoconference interviews with other contractors nationwide followed the jobsite interview.

The findings in the qualitative research phase provided the insights on attitudes toward 3DCP technology needed to develop a robust questionnaire for the survey phase of the research project. The intent of the survey was to quantify the strength and relevance of barriers and opportunities to adopting 3DCP technology, which, in turn, would provide guidance to the industry regarding desired product features and technology enhancements, optimized messaging, factors influencing adoption, and other critical topics.

Survey Sample: Home Innovation's Panel of Construction Pros

Home Innovation has decades of experience surveying construction professionals about their willingness to adopt new materials and technologies, primarily in support of building product manufacturers seeking to explore opportunities for new products and technologies. To facilitate regular surveys of builders and contractors, Home Innovation maintains a research panel of construction professionals who take part in surveys, interviews, and focus groups on industry topics. More than 3,000 construction panel members have completed one or more research assignments in the past 3 years. Panel members represent all 50 states and are a cross-section of home builders of all operating forms (custom and production) and building types (single-family detached and attached homes, apartments, and nonresidential buildings).

To encourage participation in this survey on 3DCP technology, respondents were given a $30 cash incentive, which is customary for a survey of this length. About 3,000 participants were invited to take the survey—389 responded to the invitation, and 302 went on to qualify and complete the questionnaire. Due to the relatively small sample size of this survey, Home Innovation recommends exercising caution when interpreting the findings of this study—only modest differences in scores are unlikely to represent real differences considering the margin of error for sample surveys.

Characteristics of Survey Participants

All qualified respondents were required to have a decisionmaking role in their companies, with influence to select building materials the company uses. Most participants were executive managers in or owners of their companies. Others reported functional titles related to project or construction management, purchasing, or marketing.

All qualified respondents were either builders of new single-family homes or new multifamily buildings. Many qualified respondents also reported performing remodeling (66 percent) and light commercial building construction (19 percent) in addition to their company's new homebuilding activities. In terms of home types, respondents reported building single-family detached starter, move-up, luxury, custom, semi-custom, and production homes across all 50 states and in each of the eight International Energy Conservation Code climate zones (exhibit 1).

Exhibit 1. Percentage of Single-Family Homes Participating Builders Constructed

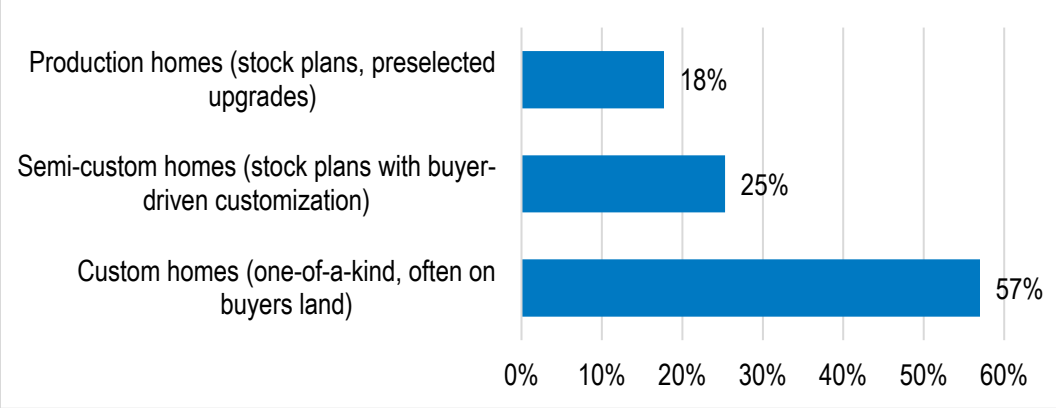


Exhibit 2 summarizes the number of completed questions from specific U.S. regions, Census Divisions, and Home Innovation's designated State-Market-Areas, which combine states with less new homebuilding activity with similar climate and geographic characteristics. Completed questionnaires were submitted from all states except Vermont.

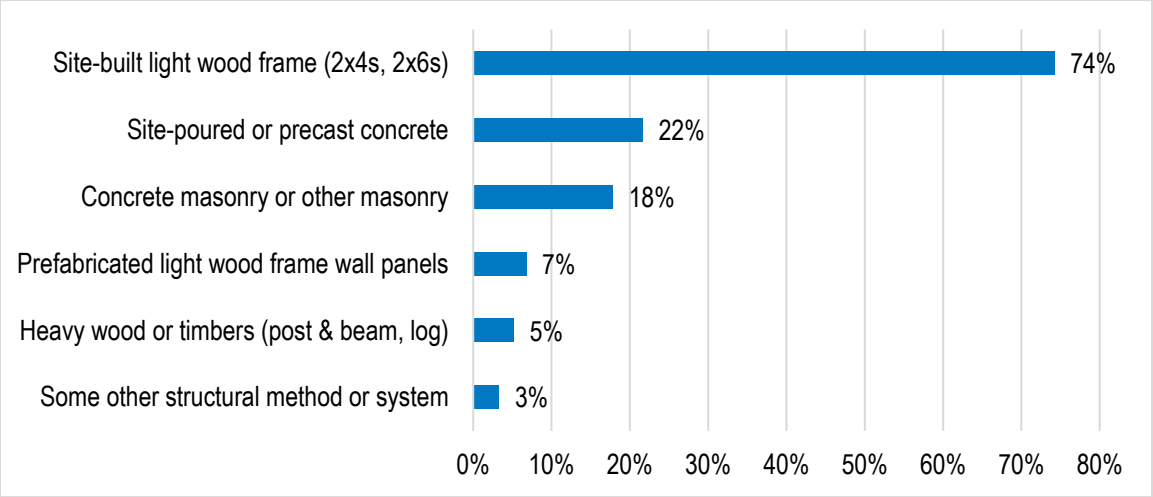
Exhibit 2. Survey Responses by Region, Census Division, State-Market-Area

NORTHEAST	69	MIDWEST	108	SOUTH	141	WEST	74
New England	**20**	**East North Central**	**71**	**South Atlantic**	**83**	**Mountain**	**45**
CT, MA, RI	16	IL	20	DE, MD, DC	8	AZ, NV, NM	18
ME, NH, VT	4	IN	13	FL	21	CO, UT	17
		MI	16	GA	10	ID, MT, WY	10
		OH	11	NC, SC	25		
		WI	11	VA, WV	19		
Mid-Atlantic	**49**	**West North Central**	**37**	**East South Central**	**30**	**Pacific**	**29**
NJ	21	IA, NE	10	AL, MS	14	CA, HI	14
NY	11	KS, MO	14	KY, TN	16	OR	4
PA	17	MN	5			WA, AK	11
		ND, SD	8				
				West South Central	**28**		
				AR, OK	8		
				LA	7		
				TX	13		

Methods and Materials Used to Construct Above-Grade Exterior Walls

Survey responses on the types of wall materials and methods currently used to construct above-grade walls were generally reflective of the types used by builders across the country. In the questionnaire, respondents were asked to select the wall types they had used to construct homes within the past 12 months (multiple responses were accepted). A strong majority reported site-built light wood frame. On average, respondents selected about 1.3 different wall materials, meaning that most respondents reported a single above-grade wall material. Exhibit 3 indicates the percentage that each was chosen by respondents.

Exhibit 3. Respondent-Reported Structural Exterior Wall Materials



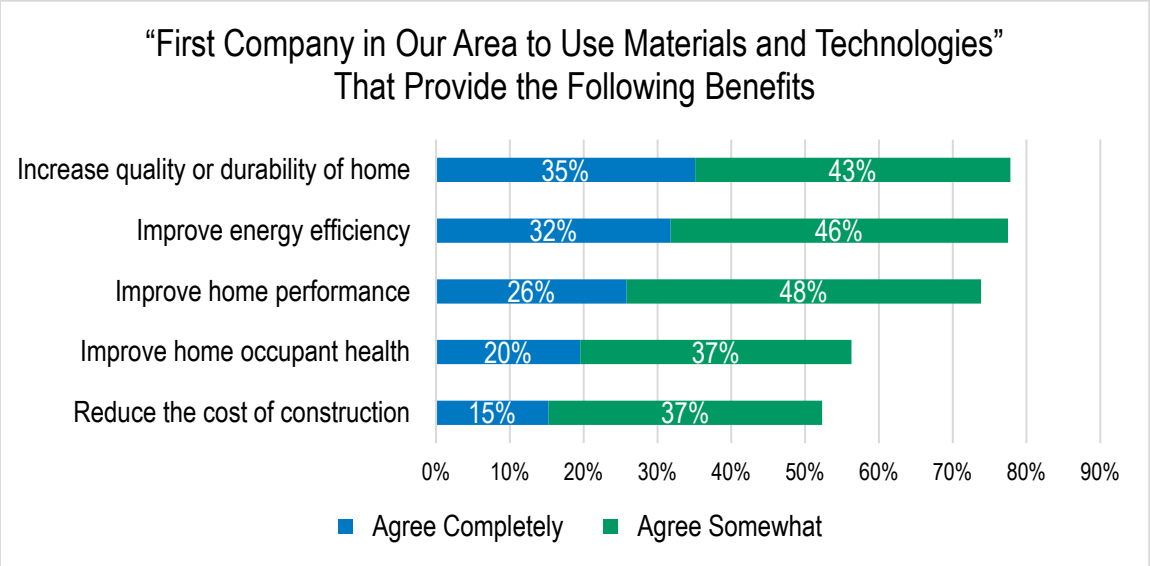
Thirty-one percent of homes built in the West were reported to be built using site-poured or precast concrete, compared with homes built in the South, where it was reported for 18 percent of homes. Respondents identifying as multifamily builders reported using prefabricated light wood-frame wall panels at twice the rate of single-family home builders.

Self-Assessment of Innovativeness

Home Innovation surveys of builders adopting new technology often ask respondents to answer a question that serves as a self-assessment of their company's innovativeness on various attributes of homes and homebuilding. This survey asked builders to rate their agreement on a five-point scale, with a statement that they are typically the first in their area to use construction materials or technologies that improve homes in (1) quality and durability, (2) energy efficiency, (3) home performance, (4) occupant health, and (5) cost reduction. This question allows us to associate the categories of innovativeness with the likelihood of adopting 3DCP technology.

Depending on the attribute of innovativeness, 15 to 35 percent of builders "agree completely" that they are the first in their area to implement practices that are innovative, as exhibit 4 shows. More than any other type of innovation, builders in the survey said they were first to increase the quality or durability of homes. Overall, they were least likely to choose an innovation that reduces cost.

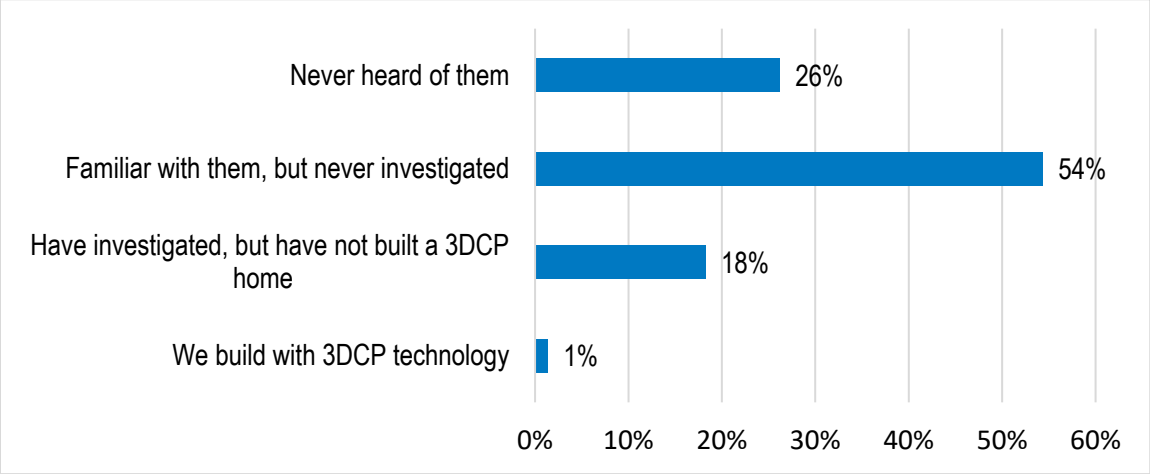
Exhibit 4. Self-Assessment of Company Innovativeness



Builders Receptiveness to 3D Concrete Printed Wall Systems

During the survey, respondents were shown a single photograph of a finished 3DCP home and were asked how familiar they were with this type of home. Overall, a percentage with some familiarity or experience with the technology (74 percent) was fairly high, but only a few respondents (1 percent) had built a home with 3DCP technology (exhibit 5).

Exhibit 5. Familiarity With 3DCP Homes



3DCP = three-dimensional concrete printing.

One-half of participants were familiar with 3DCP technology but had never investigated it. Only 18 percent said they had investigated 3DCP technology. One-third (33 percent) of those who had investigated or built with it were larger volume builders and multifamily townhome and duplex builders. In terms of regional differences, builders from the Northeast and West were most likely to have built or investigated 3DCP homes, 23 and 26 percent, respectively.

Willingness to Adopt 3D Concrete Printing Technology

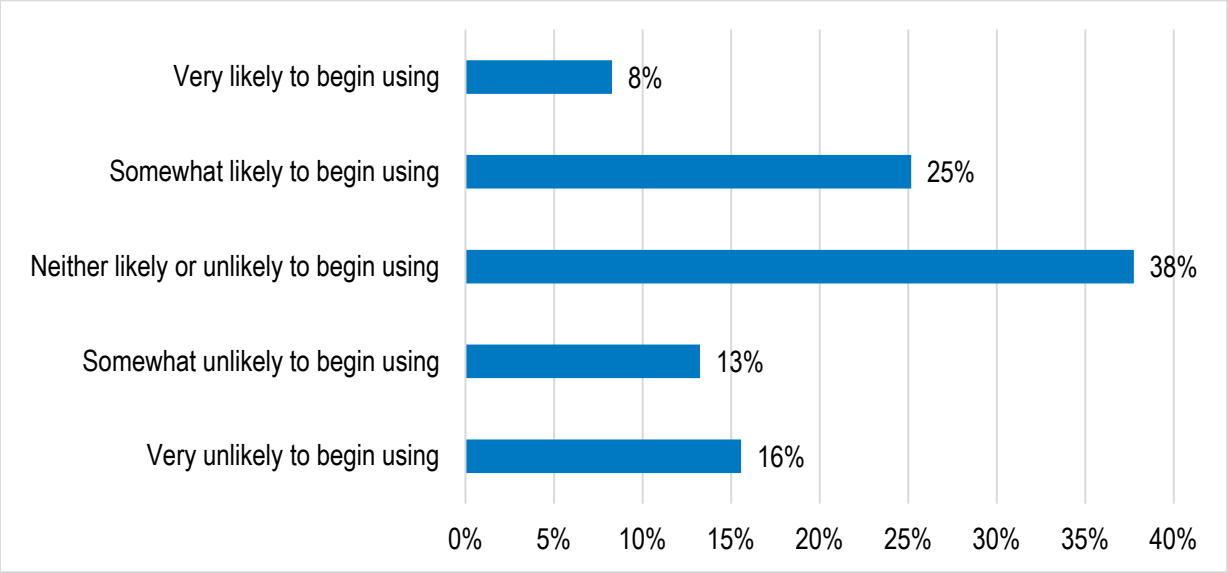
Survey participants were shown photographs of a 3DCP house during construction and photographs of completed home interiors and exteriors. They were then asked to read a fairly

neutral description of the technology that included the general process, features, benefits, and limitations, followed by a 2-minute video summarizing the 3DCP installation process. After this introduction to 3DCP technology, survey participants were then asked:

> *How likely are you to begin using 3D Concrete Printed construction methods when they're available in your area?*

Respondents were asked to select one of five responses best describing their likelihood of using the technology. Exhibit 6 summarizes the responses.

Exhibit 6. Likelihood to Adopt 3DCP Technology When Available



About one-third of respondents reported that their companies are either somewhat or very likely to begin using 3DCP technology in the future, slightly more than those reporting they are somewhat or very unlikely. The greatest number respondents chose the neutral answer—neither likely nor unlikely.

The likelihood of using 3DCP technology based on company characteristics differed. Apartment and condominium builders (48 percent) and single-family builders who operate within a regional or national geographic scope (58 percent) responded most favorably to 3DCP technology, considering themselves either very or somewhat likely to use 3DCP. Also, all builders who rated highly in the innovativeness self-assessment (exhibit 4, "agree completely") were substantially more likely to adopt 3DCP technology than those who did not, and among this group, the likelihood of adopting was greatest among those whose innovation emphasis was cost reduction (52 percent were Somewhat or Very Likely to adopt 3DCP). This association suggests that cost-savings may be a key driver to widespread adoption of this technology.

Builders who reported using concrete in above-grade wall construction in the past year and builders operating in climate zones 1 and 2 also scored high—both at 43 percent, selecting very or somewhat likely. Likewise, builders in the West and those building single-family starter homes responded more favorably about future use of 3DCP than other regions and price points.

Reasons for High Willingness to Adopt 3DCP Technology

Respondents who replied "very likely" or "somewhat likely" to begin using 3DCP construction methods in exhibit 6 were asked this open-ended question with a blank space to provide their answers:

> *In a previous question, you said you were somewhat or very likely to adopt 3DCP when it's available. What are your primary reasons for adopting 3DCP construction?*

The researchers then coded the 101 open-ended responses received into general response categories to be tabulated. Some builders mentioned more than one category, and in these cases, each reason was counted as one observation. Exhibit 7 summarizes the proportion of builders mentioning each response category.

Exhibit 7. Primary Reasons for Adopting 3DCP Construction

Response Categories	Mentions
Speed of construction / Fast / Efficiency	27%
Durability / Higher quality / Structural integrity / Strength	25%
Labor shortage solution / Labor savings	23%
Cost savings	22%
Innovative / Exciting / It is the future of building	18%
Time savings	14%
Streamlining of the construction process	7%
Customer demand / Market acceptance	7%
Design flexibility	5%
Energy efficiency	5%
Quality control / Accuracy	5%
Easy installation	4%
Material availability / Material savings	4%
Greater disaster resistance	3%
Environmentally sustainable / Beneficial to our climate	3%
Code compliant	2%
Equipment and contractor availability	2%
Affordable housing	1%
Better insulation	1%
Fire resistant	1%
Safer than traditional building methods	1%
To get away from wood frame construction	1%

Benefits involving construction speed, labor savings, strength, durability, and cost savings were at the top of the list. Viewing 3DCP as a solution to a lack of skilled, reliable labor was mentioned numerous times. The Innovative and Future of Building categories included responses that referred to 3DCP as a new or advanced technology, innovative, the wave of the future, interesting, exciting, and high-tech.

The following are some samples of the write-in responses collected.

> *This is amazing! Technology is really coming a long way. I love this concept, the time it takes to "build" a home is drastically reduced. I love that you can get unique angles and*

curves that you would normally have difficulty constructing without this type of technology. It would cut down on man hours and material costs.

High quality of finished product. Love the ability to have several selections for finishing details, and it seems to be an efficient, mainstream method that once subcontractors are acclimated would save time.

I can see the advantage of construction cost savings and energy efficiency.

If clients want this, we would be willing to try it. Cost and code compliance would need to be determined.

Labor is a problem in the area where I build. This could solve the labor shortage of framers.

Modern, fast, convenient, high-tech, the potential to save so much time and money on a build while delivering high-quality built homes.

Structural for Wind Loads if the cost is not out of line with conventional construction and meets Florida codes.

Reasons for Low Willingness to Adopt 3DCP Technology

Respondents who replied "very unlikely" or "somewhat unlikely" to begin using 3DCP construction methods shown in exhibit 6 were asked this open-ended question with a blank space to provide their answers.

In a previous question, you said you were somewhat unlikely or very unlikely to adopt 3DCP even when it's available. What are your primary reasons against adopting 3DCP construction?

Eighty-seven respondents replied to this question. These open-ended responses were then coded into general response categories so they could be tabulated in the same manner described for the previous write-in question. Exhibit 8 summarizes the coded responses.

Exhibit 8. Primary Reasons Against Adopting 3DCP Construction

Response Categories	Mentions
Cost of construction, equipment, and materials	33%
Learning curve of new technology / Technology is too new and still evolving / Would rather wait until other builders in area use it and can speak about using it	24%
Lack of customer demand	22%
Subcontractors and trades are unfamiliar with technology / No contractors available in my area	14%
Lack of design and finish flexibility / Remodeling would be difficult / Seems more difficult than it's worth / Too similar to poured concrete walls	13%
Appearance is not desirable / Prefer wood frame to concrete / Not interested	9%
Doubt envelope is energy efficient in a cold climate / Won't keep out moisture / Quality	7%
It would be hard to get large equipment to our remote and sloped housing lots	6%
Concerns about building code compliance and inspections	5%

Response Categories	Mentions
Need more information on cost	5%
Need more information on 3DCP technology	5%
Availability of concrete and materials	3%
Need to see it in person first	2%
Speed of setup	2%
Too late in career to try	2%
Does not fit our building model	1%
Need buy in from executives and owner	1%
Need more information about thoughts from agents and buyers	1%
My area is behind on this technology	1%

Many of the responses indicated a need for more information about the cost or the technology in general, primarily the cost of acquiring the equipment and skills needed before adopting it. Furthermore, some builders want to see it in person first or want to see it demonstrated by other builders. Many believe it is still a new and evolving technology, and they do not want to be the first to adopt it. Others said they need to hear their homebuyers ask for it.

The following are some samples of the write-in responses.

> *Cost I believe is high. The availability of concrete is not strong at the moment. Customers know very little about this. Trades don't know much about this. Large learning curve on everyone's part.*
>
> *House sites are usually small, hard to get to and sloped in our Appalachian Mountain region. Getting the equipment to a site and setting it up would be very difficult.*
>
> *I think the technology is still evolving and may take some time before I feel comfortable to use.*
>
> *I'm dubious that a 3DCP will be able to operate in the rugged mountain topography of our area.*
>
> *Lack of market acceptance to modern designs.*
>
> *We are typically not the first in our market to use 'new' construction practices without a lot of research and time to see how it works out for others.*

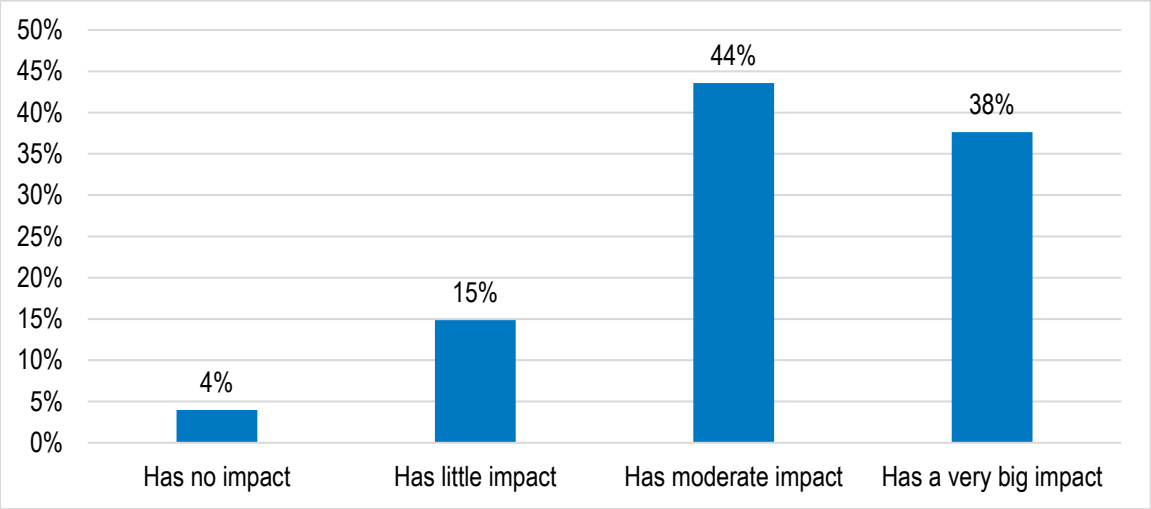
Impact of Lumber and Sheathing Prices on Adopting 3DCP Technology

The team posed another followup question to those responding "very likely" or "somewhat likely" relating to the price of lumber and wood sheathing panels. The question was particularly important and relevant due to the abnormally high prices of lumber and sheathing panels during the previous year. It was important to gauge if a decline in the price of lumber may slow demand for 3DCP technology. The team asked—

> *How much does the price of lumber and wood sheathing panels impact your likeliness to adopt 3DCP?*

Exhibit 9 summarizes the responses to this question.

Exhibit 9. Lumber and Wood Sheathing Costs on Likelihood of Adopting 3DCP Technology

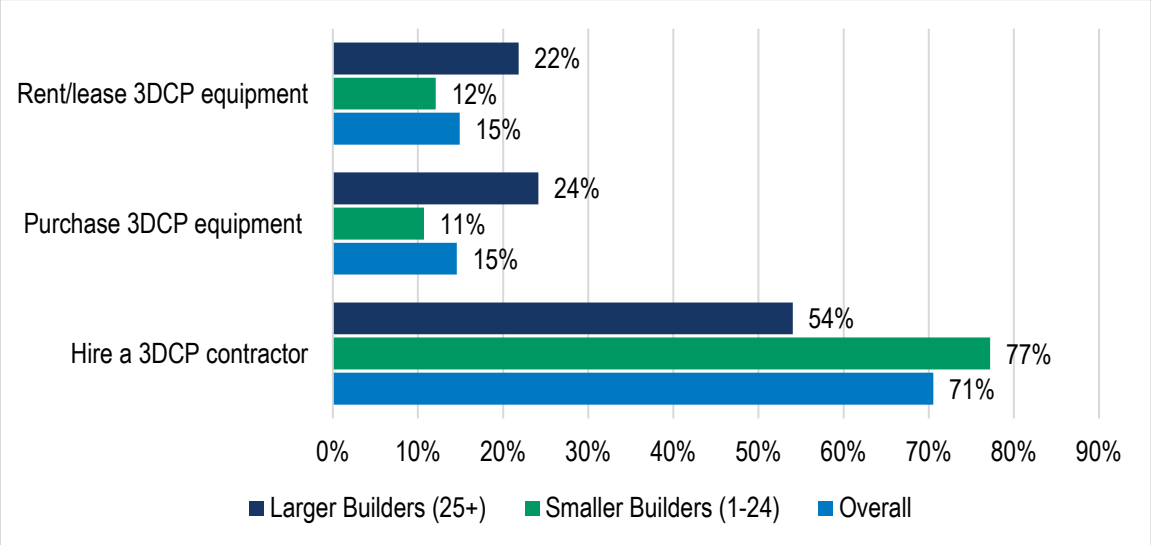


More than three-fourths (82 percent) of respondents who indicated they are "very likely" or "somewhat likely" to adopt 3DCP construction methods stated that the price of lumber will have a moderate to very big impact their decision to do so. The price of lumber at the time of fielding the survey was higher than historical prices but lower than peaks during the post-COVID supply chain crisis. The primary point in this line of inquiry is that adopting 3DCP technology may decelerate on a national level if the price of lumber and sheathing drops substantially.

Business Arrangement for 3DCP: Equipment and Installation

Respondents were asked which would be the best business arrangement for building 3DCP homes or buildings if their company chose to adopt the technology. Exhibit 10 shows the responses.

Exhibit 10. Best Arrangement for Building 3DCP Homes



3DCP = three-dimensional concrete printing.

In the overall sample, 71 percent of respondents preferred hiring a 3DCP contractor. The remaining respondents were split equally between purchasing and leasing equipment (about

15 percent each). However, preferences by size of builder differed. Preference for purchasing and leasing equipment was about twice as high among larger builders (25 or more completions per year) compared with smaller builders (24 or fewer per year).

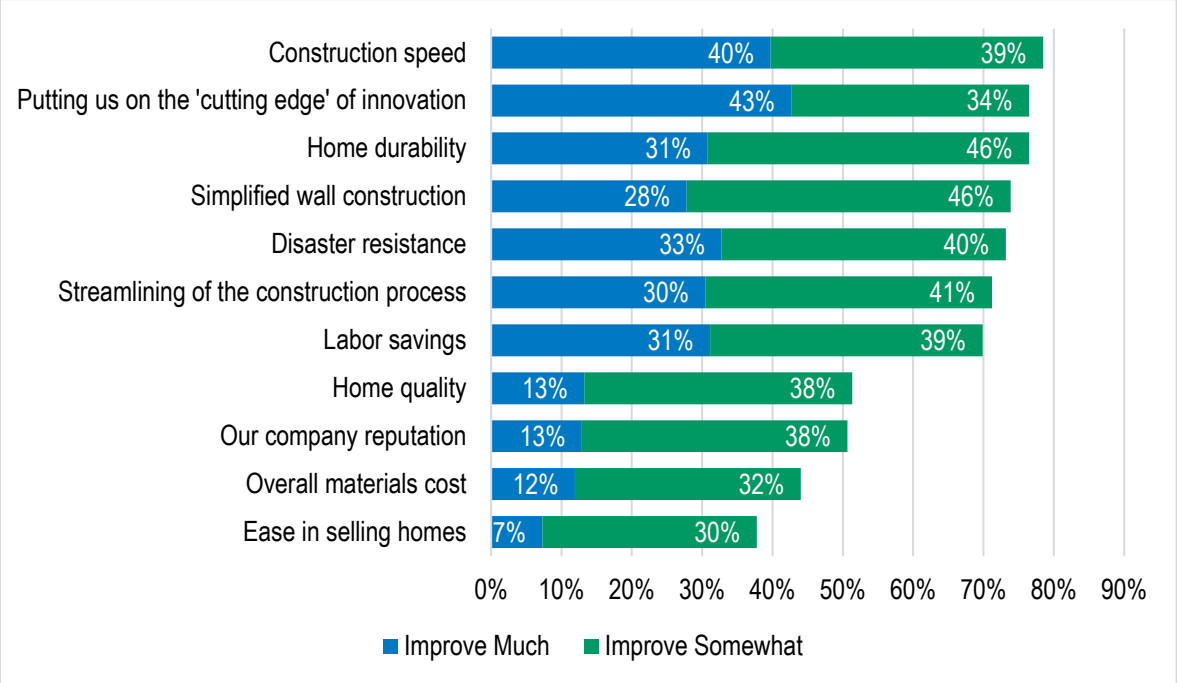
Perceived Business Improvements from Adopting 3DCP Technology

In further development and marketing of 3DCP technology, it is important to understand the benefits and drawbacks it will bring the builders. Promoting the technology should focus on improvements made as a result of adopting it. The negative effects (either real or perceived) should be addressed in product design and communication to those potentially adopting 3DCP technology. In this study, respondents were asked—

> *Do you think 3DCP construction methods, if adopted by your company, will generally improve, make worse, or have no impact on each of the following aspects of constructing homes and operating a homebuilding business?*

The team provided respondents a list of 11 aspects of home performance and construction—these aspects were generally uncovered in the qualitative research phase of this project. Respondents were asked to rate each aspect as "much improve," "somewhat improve," "no difference," "somewhat worse," or "much worse." Exhibit 11 summarizes the responses of those choosing "much" or "somewhat improve."

Exhibit 11. Effects of 3DCP Construction Methods on Home Construction



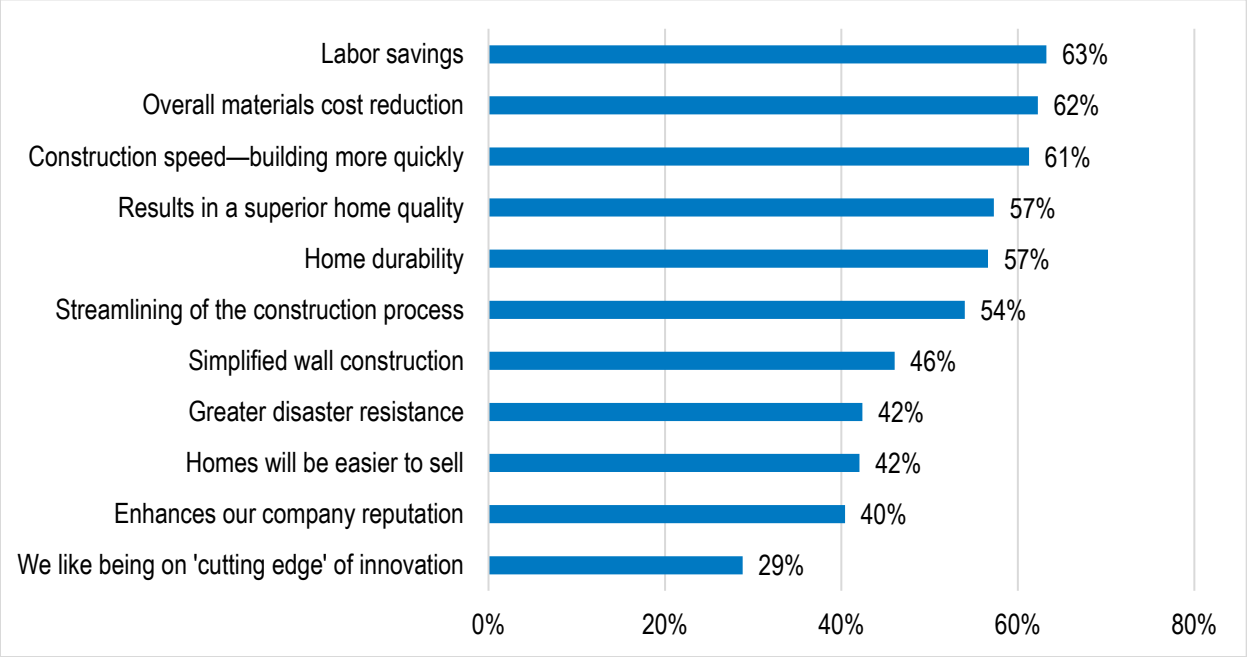
Combined, the related benefits of speed, simplification, streamlining, and labor savings finished at or near the top. The related benefits of a 3DCP home's durability and disaster resistance are also in the top tier, likely due to its concrete construction. Only 13 percent of builders expect significant cost-savings in materials. At the bottom of the list, only 7 percent of builders reported that they believe "ease in selling homes" would improve much with 3DCP technology.

Importance of Potential Benefits From Adopting 3DCP Technology

The next question was designed to help measure the importance of potential benefits rising from adopting 3DCP technology. Survey respondents were asked to rate the importance of each potential benefit they reviewed in the previous question. Importance scores were then compared with the perceived improvements in business and home performance from 3DCP technology to establish whether it provides the benefits builders value most.

When both the importance and perceived benefits of 3DCP technology are high, these benefits should be heavily promoted to potential users. When the importance is high, but the perceived benefit is modest or small, 3DCP technology suppliers need to bridge this gap with product improvement or enhanced communication efforts. Exhibit 12 summarizes the share of respondents rating the benefits of this technology as "very important."

Exhibit 12. Potential Benefits of 3DCP to Companies



Respondents rated labor savings and overall material cost reduction as the top two benefits, with construction speed following closely. By comparison, in exhibit 11, construction speed rated highly as a perceived benefit, construction labor savings finished toward the middle of responses, and materials cost reduction was near the bottom. Based on a comparison of exhibits 11 and 12—with the gap between the high importance of material costs and low perceived benefit—material costs will likely be a barrier that 3DCP equipment and material manufacturers will need to overcome before achieving widespread adoption. On the other hand, the perceived 3DCP benefit of improved construction speed rated highly, and its importance rated highly as well. This rating signals that an emphasis on construction speed in messaging will be well received and could be the primary driver of adoption, particularly among builder types that this most benefits, such as production builders. More than one-half of builders rated home durability as very important, which aligns with the perceived benefits high score, so effective messaging should also emphasize this characteristic. Unsurprisingly, builders who said they were the first in their area to improve home performance and reduce construction costs are particularly keen on 3DCP technology's potential benefits.

Most Promising Construction Applications for 3DCP

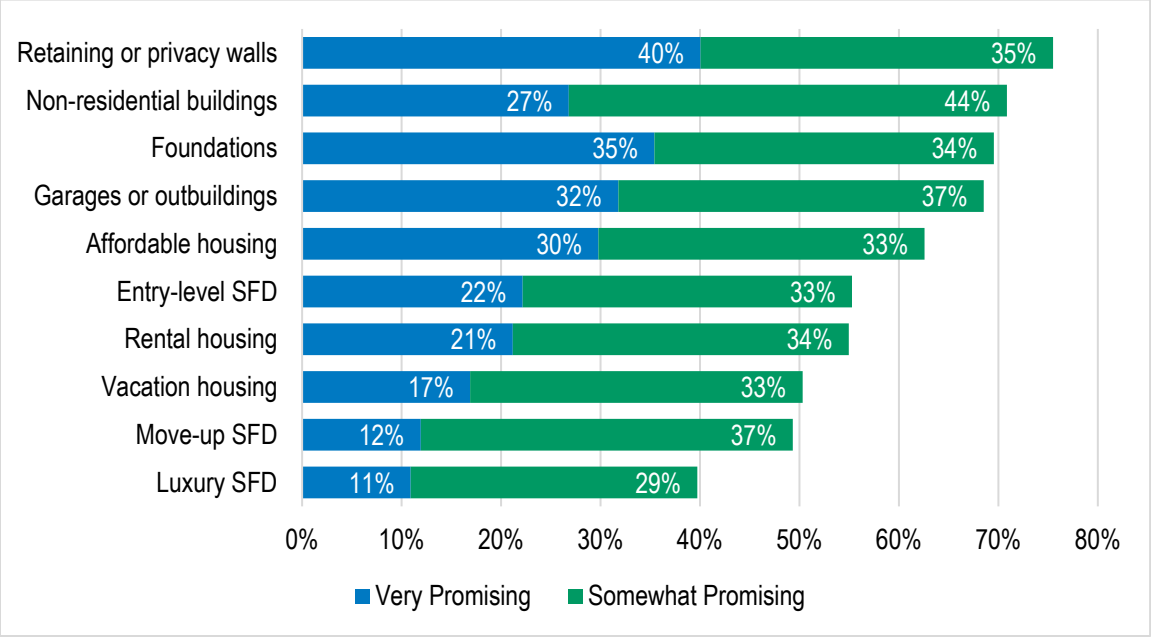
Very often, developers and marketers of new construction technologies select their target market based on limited experience across the full breadth of construction applications or because their business planning requires a large "total addressable market" to reach investor financial objectives. With 3DCP technology, most companies seem to be attracted to the structural, above-grade residential walls market opportunity.

Home Innovation asked survey participants to rate how applicable 3DCP technology was for a wide range of construction applications and market segments. Interestingly, applications outside of single-family residential dwellings were among the top choices. The questionnaire asked:

> *In which of the following construction applications do you see 3DCP technology as being a promising solution?*

For each potential application of 3DCP technology, respondents had the choices of "very promising," "somewhat promising," "neither promising nor unpromising," "somewhat unpromising," and "very unpromising." Exhibit 13 summarizes the overall findings of those who selected applications as promising.

Exhibit 13. Most Promising Applications for 3DCP Technology



SFD = Single Family Detached.

According to the overall findings, 75 percent of builders saw 3DCP technology as a promising solution for retaining and privacy walls. This response was especially true in the West, where masonry or concrete privacy walls are very common. Also, simpler or less refined structures—such as foundations, garages, and affordable housing—finished near the top. Among the housing options, affordable housing received the most positive rating, with 63 percent selecting this category as either very or somewhat promising. Among single-family detached housing price-points, entry-level homes received the highest rating. Luxury homes rated the lowest, with only 11 percent of respondents considering it a very promising application.

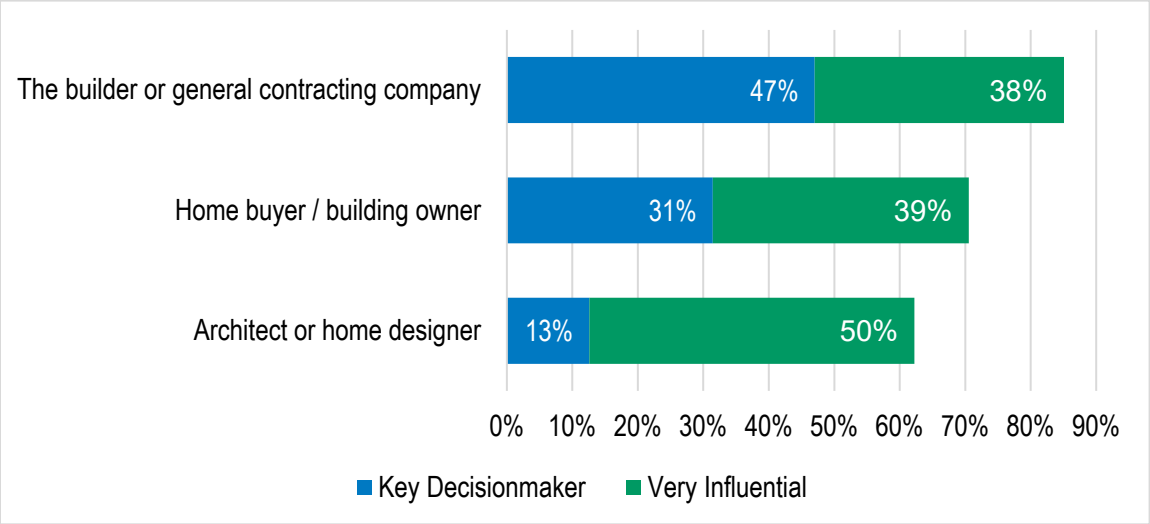
For affordable housing, builders in the West rated entry-level single family detached as very promising at 34 percent, although builders in the Northeast and Midwest rated the technology as very promising for the same housing type at only 18 and 17 percent, respectively.

In light of these findings, the team recommends that 3DCP suppliers broaden their view of potential applications. Applications that rated among the most promising were those with simpler wall configurations that have minimal openings or little need for plumbing and electrical utilities. The most promising applications were those that had less need for design, with appearance being less crucial, or where the concrete ribbon appearance is acceptable or preferred. Although any one of these applications may not take full advantage of 3DCP technology potential, they can have a lower threshold for gaining acceptance and can help it get a foothold in the market while the technology, contractor base, and supply chain become better established.

Understanding Influencers of Adopting 3DCP Technology

A clearer understanding of who will influence the decision to adopt 3DCP technology can allow suppliers to frame the messaging to target the right audience and design the most effective marketing communication campaigns. This study finds that builders or general contracting companies are by far the most influential segment in the decision to incorporate 3DCP construction into future projects (exhibit 14). Homebuyers were also said to exert some level of influence in this decision, but they are only the primary decisionmaker among one-third of responding builders. Although architects were seldom noted as key decisionmakers, they are still "very influential," according to one-half of the respondents.

Exhibit 14. Most Influential Decisionmakers in 3DCP Technology Adoption

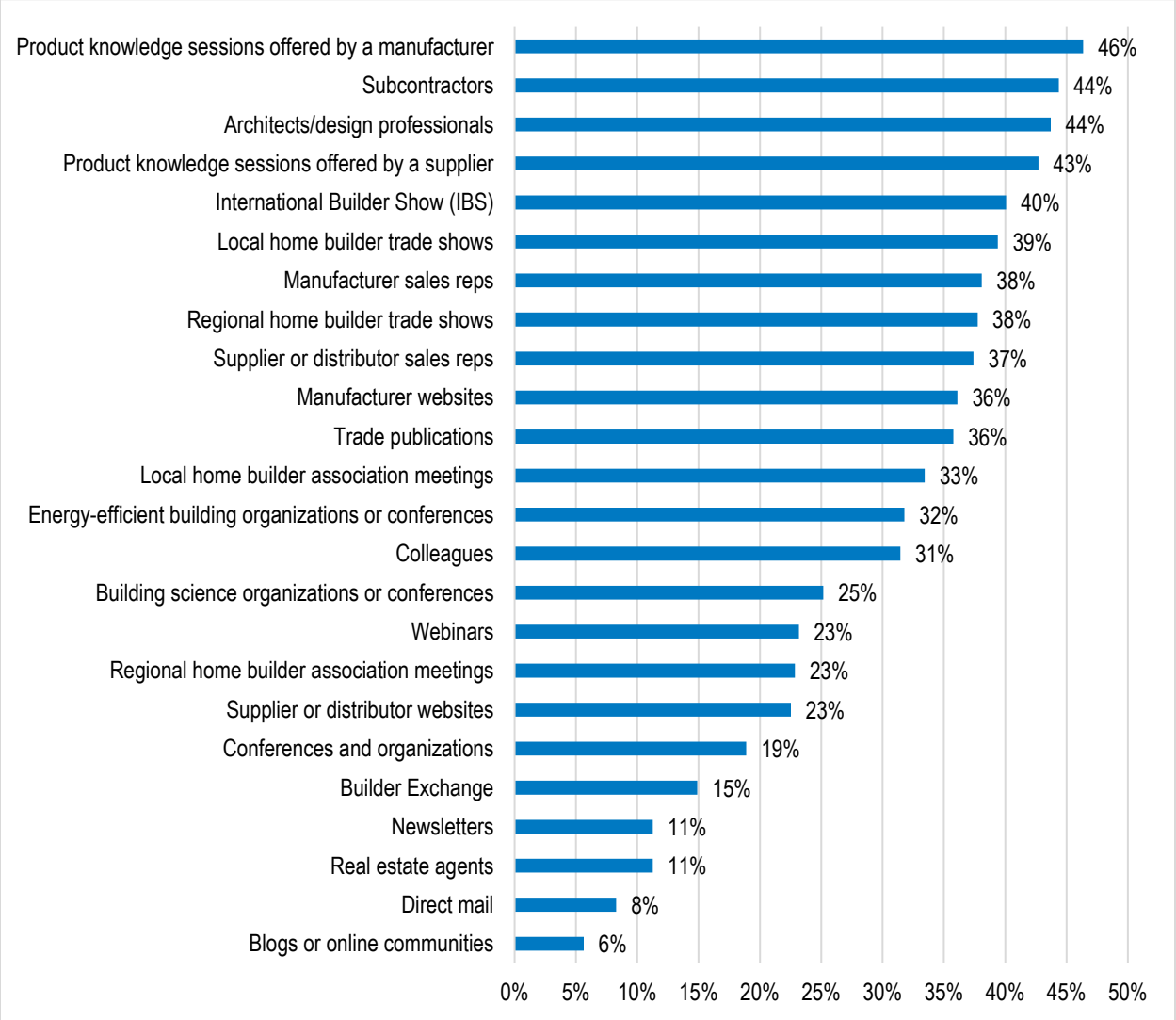


Importance of Resources in Evaluating 3DCP Technology

When investigating 3DCP or any new technology, builders rely on numerous resources to help evaluate whether it is right for their companies. This survey asked builders to choose important resources in their evaluation process and presented them with a comprehensive list of information sources, learning venues, and media from which to choose (exhibit 15). With respect to information sources, manufacturers and suppliers of 3DCP systems, subcontractors, and architects/design professionals were among the top choices builders say they rely on. For learning venues, in-person industry trade shows, conferences, and building association meetings

rated in the middle and upper tiers. Furthermore, substantially more builders selected websites and webinars than newsletters, blogs, online communities, and direct mail.

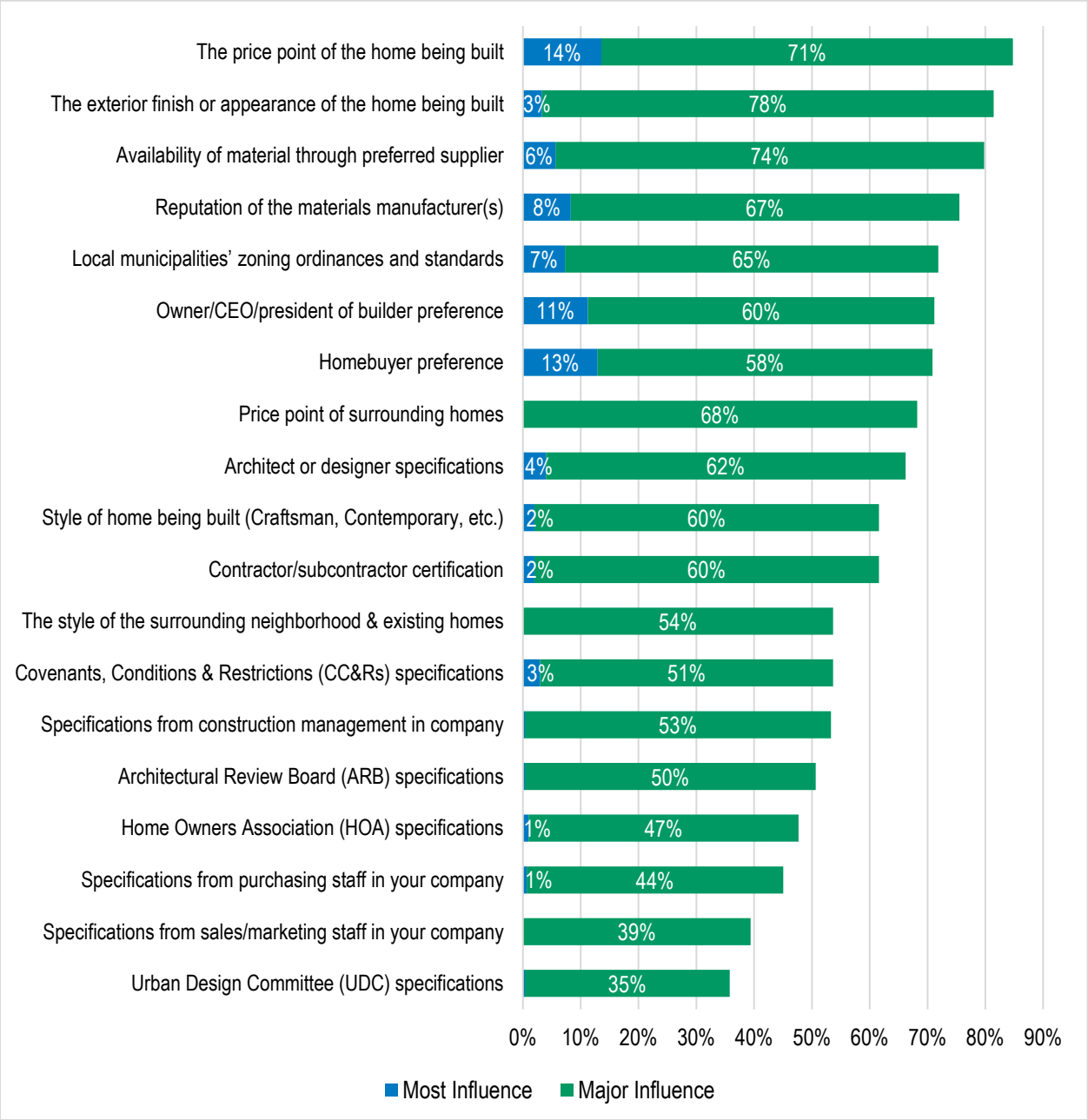
Exhibit 15. Sources Potentially Influencing the Type of Wall Assembly



Factors Influencing Choice of Structural Wall System

Many factors outside the attributes of the materials and technology also influence builders' choice of materials for exterior wall assembly on specific projects. The survey contained a question to gauge the importance of these exogenous factors, including a list developed from the qualitative research phase and from Home Innovation's extensive previous "diffusion of innovation" research. When presented with the factors, respondents were given the choice to rate each as "most influential," a "major influence," "minor influence," and "no influence." Exhibit 16 summarizes the factors selected as "most influential" and "very influential."

Exhibit 16. Factors Influencing Type of Wall Assembly in New Homes



One notable point about this segment of the questionnaire is the large volume of factors that must be considered in selecting wall assembly types, indicating the complexity of the decision. In 15 of the 19 categories, more than one-half of builders stated these factors were major influences or more.

The price point of the home is at the top of the list—that is, entry-level, move-up, or luxury home—finishing with the greatest number of "most influence" choices. This response was followed by homeowner preference (13 percent rated as "most influence") and building company owner, chief executive officer, or president preference (11 percent as "most influence"). When considering factors of "major influence," 78 percent of respondents rated "exterior finish or

appearance of the home being built," and 74 percent rated "availability of the materials through preferred supplier" at this level of influence.

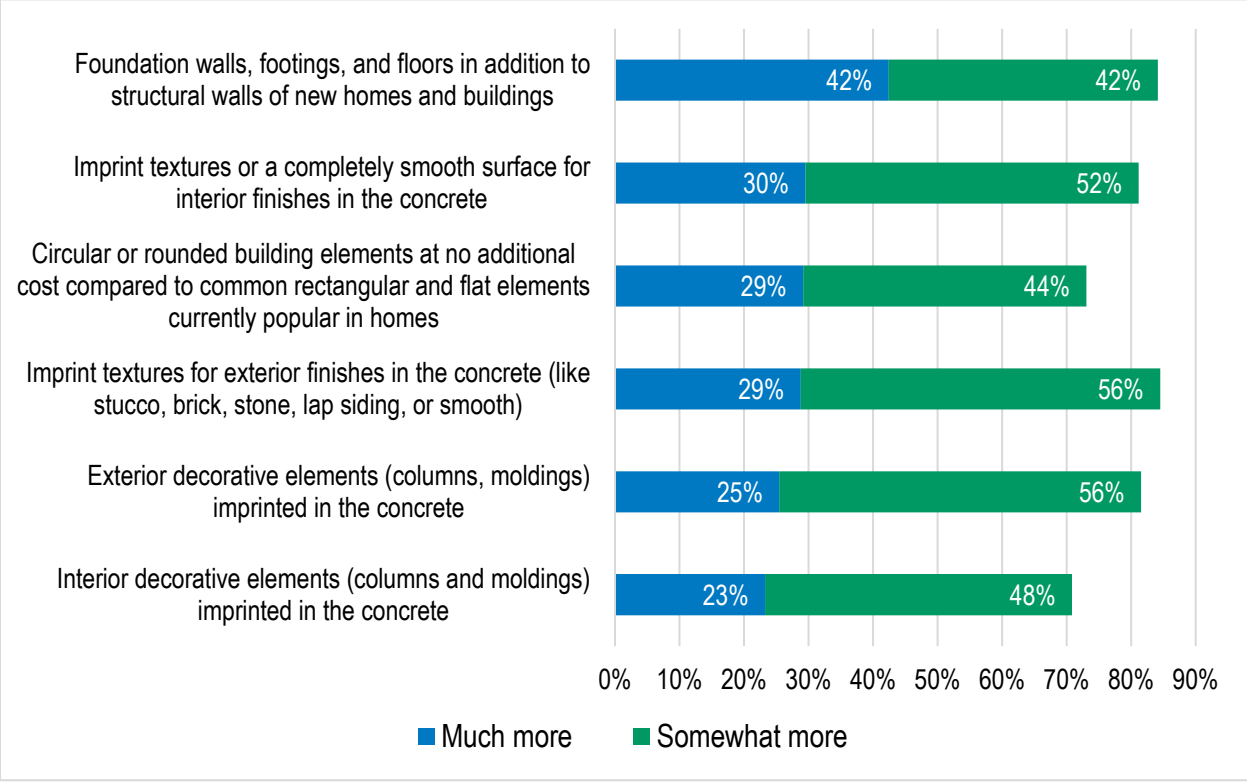
Features That Could Accelerate Adoption of 3DCP Technology

Most extant 3DCP technologies allow for printing of above-grade walls for buildings that have a "ribbon" texture. Given the flexibility to control features of 3DCP appearance in interior and exterior elements and print more elements in the house, researchers added a series of six questions to the survey to assess whether any of these features, if included in the 3DCP package, would increase their likelihood of adopting the technology. The six additional features were—

- Foundation walls, footings, and floors.
- Smooth or textured interior surfaces.
- Circular or rounded building elements.
- Textures (like stucco, brick, and so on) for exterior finishes.
- Exterior decorative elements (columns and moldings).
- Interior decorative elements (columns and moldings).

Exhibit 17 summarized the responses of those who chose "much more" and "somewhat more" likely to adopt 3DCP technology in reply to this question.

Exhibit 17. Likelihood of Adopting 3DCP Technology if Additional Features Were Added



Overall, the added features to 3DCP technology seem to boost the likelihood of builders adopting it. Forty-two percent of respondents stated they would be much more likely to adopt 3DCP technology if it had the capability to provide "foundation walls, footings, and floors" in addition to walls. The following three features, receiving 29 or 30 percent "much more" likely

ratings, related to home appearances—were the inclusion of smooth or textured interior, exterior finishes, and circular and rounded building elements.

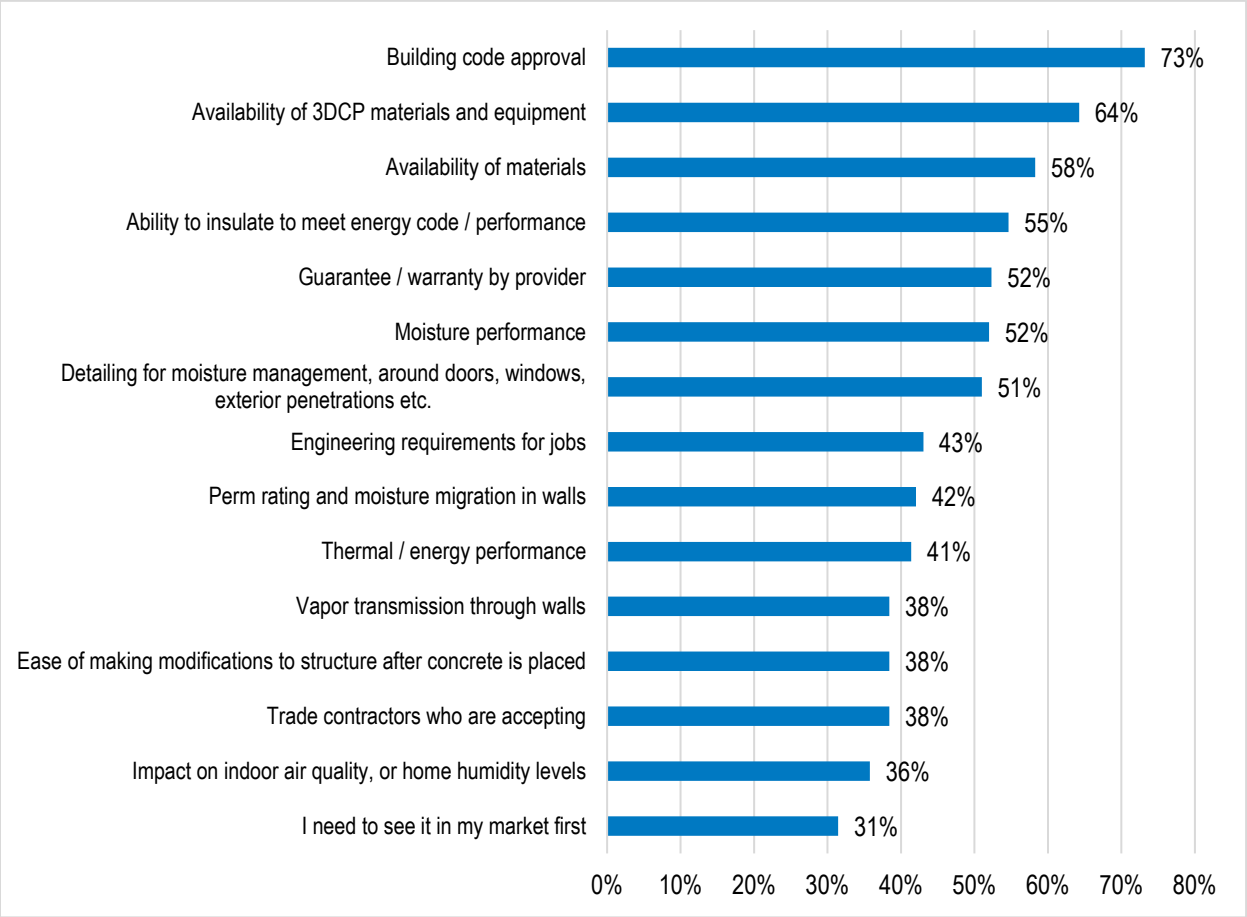
Barriers in 3DCP Technology: Information Needs and Assurances

The survey also asked builders questions about the barriers they face and the need for additional information before adopting 3DCP construction methods. The first question was—

> *For which of the following will you need to gain assurance or develop a deeper understanding of 3DCP before deciding that this construction technology is right for your company?*

A list of 15 possible topics or issues gathered from the qualitative research phase and researchers' prior experience followed this question, allowing respondents to rate each as "crucial," of "major importance," of "minor importance," and "not at all important." The sixteenth issue was a write-in response for which builders were allowed to include any issues not in the list. Exhibit 18 summarizes the share of builders choosing "crucial" for each of the 15 defined topic areas and issues.

Exhibit 18. Crucial Needs to Gain Assurance or Develop a Deeper Understanding of 3DCP



3DCP = Three-Dimensional Concrete Printing.

Overall, assurances of building code approval ranked at the top, with nearly three-fourths of builders rating it as crucial, and 64 percent of respondents rated availability of 3DCP materials and equipment as crucial. Building code approval was particularly crucial for those who stated

they are the first in their area to increase quality, durability, performance, and energy efficiency, but this was also true for smaller and custom home builders. Builders in the South also required the most assurance about the availability of 3DCP materials and equipment or materials in general more than other regions. Builders using site-poured or precast concrete were closely aligned with the total survey sample.

The following are examples of the responses from the write-in item.

Ability to apply trim material.

Ability to build on a sloped site.

Florida is a humid state, so moisture and mildew control is the most important.

How is this going to look—the ones I looked at are not all the nice looking both inside and out. If I have to still frame on the inside to fir out walls and then tap-con in all the siding to make it look like a house, that is a lot more work and not saving me much if any time.

I am not sure how the customers would like the outside and inside look of the material. I would like to know more about how drywall would be placed inside and if the exterior could be given a stucco finish. Also, what about cracks in the walls? I know concrete is going to have hairline cracks especially in extreme temp zones.

I need to see the Seismic rating.

I would need to see an entire 3DCP build happen locally from start to finish before I would risk using this technology.

Integrating 3DCP with other building methods to customize homes.

Not sure how after-sale renovations could be made.

The installer understands thoroughly how this process works.

There are trade-offs, but the entire system and process needs to be less expensive than current traditional construction.

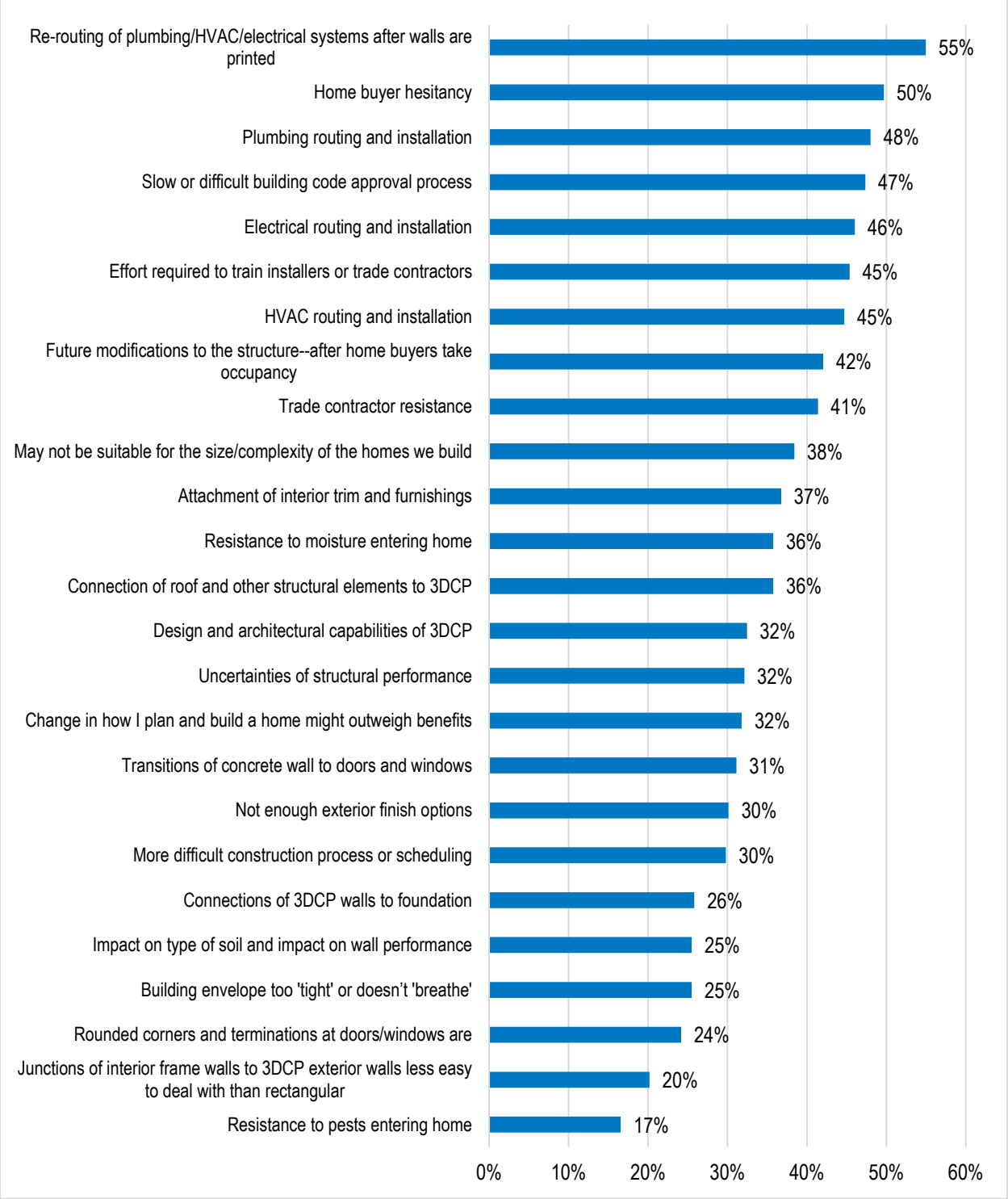
Barriers in 3DCP Technology: Issues to Address

As a continuation of the discussion on barriers to builders adopting 3DCP technology, the survey posed another question to respondents regarding their concerns that need to be addressed more thoroughly before using the technology.

To what degree do you have concerns with adopting 3DCP homes for each of the following?

The survey then provided a list of concerns, separate from the list of potential information needs in the previous question, and asked builders to choose the response that best described their level of concern for each topic as having “much concern,” “some concern,” or “no concern.” Exhibit 19 shows the percentage of respondents stating they had “much concern.”

Exhibit 19. Elements of Much Concern for Builders



3DCP = Three-Dimensional Concrete Printing. HVAC = Heating, Ventilation, and Air Conditioning.

Overall, builders voiced concern most strongly about routing and placement of electrical, plumbing, and HVAC utilities. They also had concerns about homeowner hesitancy. Furthermore, some builders were concerned about the effort required to train installers or trade contractors and potential trade contractor resistance.

Summary of Findings

The survey findings suggest that general awareness of three-dimensional concrete printing (3DCP) technology is fairly high, but only a tiny share of builders have implemented it in their construction businesses. About one-third of survey participants believed they were likely to adopt 3DCP technology it in the near future, although many stated they were unlikely to adopt it. However, the differences were substantial in the willingness to adopt it based on the size or type of builder and geographic region.

- Regional and national builders reported they were more likely to adopt 3DCP technology than builders operating only in one market area.
- Multifamily builders and those currently constructing homes with concrete above-grade walls were much more likely than average to express a willingness to adopt.
- Builders who lead their markets in cost-reducing innovations were more willing to adopt 3DCP technology than were market leaders in home quality or energy performance.
- Builders in the hottest climates (International Energy Conservation Code zones 1 and 2) were most receptive to adopting this technology.

Builders in the study reported that the biggest advantages of 3DCP technology over existing construction methods were increased construction speed, labor savings, construction process simplification, increased durability, and disaster resistance. Of these benefits, respondents said labor and cost reductions were the most important. With respect to the barriers of adopting 3DCP technology, this study shows that builders believe construction costs will likely prove to be higher than traditional construction methods and could slow its market acceptance. Respondents also indicted a belief that the learning curve will be very steep for their subcontractors—particularly the steps related to routing utilities in walls. They expressed concerns about the problems that would be created as a result of correcting mistakes in routing utilities after the concrete cures. Also, some builders reported that they expect a lack of demand among homebuyers for homes constructed using 3DCP technology.

As for improvements to expedite adopting 3DCP technology, builders in this study stated they are more likely to adopt the new technology if interior and exterior finish surfaces were offered in a variety of textures and not just the ribbon pattern. Furthermore, the speed of market adoption can be potentially increased if 3DCP suppliers were to offer the capability to print foundations and above-grade walls in a single printing. Builders saw 3DCP technology's greatest potential for use in simpler construction types, such as privacy and retaining walls, foundations, utility structures (for example, garages and outbuildings), and affordable housing. They saw the least opportunity in structures with more complex wall details, such as in luxury homes.

In this study, home builder respondents indicated needing to overcome their objections and hesitation for them to consider adopting 3DCP technology, including (1) the technology will readily meet building codes, (2) the availability of equipment and material will be widespread, and (3) the technology providers will guarantee the strength and performance of the structures. The survey findings also suggest that 3DCP construction technology has significant potential to make inroads into residential construction. To accomplish this feat, 3DCP suppliers should strategically target the most receptive technology adopters, as defined in this study, and continue to refine and enhance the technology in response to market feedback. The best way for 3DCP suppliers to inform the industry of this technology is through in-person demonstrations hosted by manufacturers, suppliers, or contractors.

Conclusions

The survey findings suggest that three-dimensional concrete printed (3DCP) construction technology has significant potential to make inroads into residential construction, particularly if 3DCP suppliers are careful to target the most receptive categories of adopters, as this study uncovers, and if the technology continues to be refined and add enhancements. Successful introduction will require convincing potential adopters that building codes can readily be met with 3DCP structures, building performance will be equal to or exceed conventional construction methods and materials, and that structures can be built cost-effectively using this technology.

HUD has a long history of facilitating the standardization of new technologies through the development of design guides with industry stakeholders—the best example is the creation of the *Design Guide: Residential PEX Water Supply Plumbing Systems*, which allowed manufacturers to standardize their plumbing products and installation practices. As a result, housing was made more affordable through the widespread use of cross-linked polyethylene, or PEX, plumbing systems.

The 3DCP construction industry will need similar HUD support, given the fact that they do not have an industry association, and most of the concrete material formulations and robotics are proprietary. The National Institute of Standards and Technology has been working with the American Concrete Institute and 3DCP technology companies to standardize both the material formulation (in terms of performance requirements) and robotics. HUD is best positioned to assist the industry with standardizing construction practices, which are critical to increasing the adoption of this technology and including it in building codes.

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