Defining a National Housing Research Agenda: Construction Management and Production

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Abstract

This paper summarizes findings from a workshop sponsored by the National Science Foundation in February 2004, the purpose of which was to define a national housing research agenda. The workshop was organized into five topical areas: 1) construction management and production, 2) structural design and materials, 3) building enclosures, energy and indoor air quality, 4) housing technology, community and the economy, and 5) systems interactions and "whole house" approach. This paper summarizes findings in the construction management and production area, summarizing the state of the art in research and recommending future research directions. In summary, metrics, methods and tools must be developed to achieve the desired improvements in homebuilding performance. Research is recommended in the following areas: 1) enhancing demand side pressure for quality, 2) developing fundamental construction theory, 3) coordinating the disaggregated supply chain, 4) developing shell and infill processes and technologies, 5) balancing off-site and on-site production, and 6) innovation in safety, quality, scheduling and cost management systems.

Keywords: housing, research, construction management, production

Introduction

On February 12, 2004 the National Science Foundation (NSF) sponsored a workshop to define a national housing research agenda. The three-day workshop was held at the University of Central Florida in Orlando. Workshop participants included 39 faculty members representing 26 universities, a researcher from the National Association of Home Builders (NAHB) Research Center, and a researcher from State Farm Insurance Companies. Representatives from NSF and the U.S. Department of Housing and Urban Development (HUD) also attended. Most faculty participants were invited as representatives of their NSF-Partnership for Advancing Technology in Housing (PATH) research teams. These participants were supplemented with a limited number of additional faculty/researchers from the universities represented in National Consortium of Housing Research Centers (NCHRC). The workshop was organized into five topical areas: 1) construction management and production, 2) structural design and materials, 3)

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building enclosures, energy and indoor air quality (IAQ), 4) housing technology, community and the economy, and 5) systems interactions and "whole house" approach. After a brief overview of the workshop structure, the paper summarizes the current state of the art in research and recommends future research directions in the construction management and production area.

Workshop discussions addressing construction management and production issues involved eight faculty members: Howard Bashford – Arizona State University, Leonhard Bernold – North Carolina State University, Makarand Hastak (co-leader) – Purdue University, Stephen Kendall – Ball State University, Joseph Laquatra – Cornell University, Michael Mullens (leader) – University of Central Florida, Avi Wiezel – Arizona State University, and Jack Willenbrock – Penn State University. Each participant prepared a position paper in advance of the workshop (Bashford 2004, Bernold 2004, Hastak & Syal 2004, Kendall 2004, Laquatra 2004, Mullens 2004, Wiezel 2004, Willenbrock 2004) and one paper was submitted by a non-participant (Abdelhamid 2004). Each position paper addressed the current state of the art of research in one or more sub-areas, including topics outside the participant's own NSF-PATH research. Finally, each paper identified future research directions in these areas. Papers were distributed to participants for their review before the workshop began.

The construction management and production topic area was discussed in three three-hour sessions. In the first session each participant presented a summary of his position paper and briefly answered questions. During the second session, participants collaborated to reach consensus on a draft research agenda. Several iterations of brainstorming, consensus building, and priority-setting were required. In the final session, draft findings were presented to participants in the systems interactions and whole house area. Comments were used to revise the draft agenda. Before concluding the workshop, a summary of the proposed research agenda was presented to all workshop participants.

State of the Art in Research

The operational performance of current housing production systems is documented in the literature. In the first statistically valid study of new home quality, researchers inspected over 400 randomly selected single-family homes completed in Central Florida during 2001. Using an extensive checklist of quality attributes, researchers searched for defects on the interior, exterior and surrounding property of each house. Results were reported in a weeklong series of front-page articles in the local newspaper (Tracey 2003) and simultaneously reported as lead stories by the local NBC television affiliate. Defects were categorized by severity as 'priority problems', 'concerns', and 'worth noting'. Priority defects were believed to pose potential health, structural, operational, and safety risks. Concerns were easily noticeable and indicative of poor quality control. Defects worth noting were largely unsightly cosmetic problems. Some summary findings are shown in Table 1. Among the root causes cited were pressures on large national builders to build too fast - 24,000 homes will be built in the Central Florida market in 2004. This pressure is passed along to local subs, staffed largely by an unskilled, immigrant labor force, who are unable to maintain the pace without sacrificing quality.

Table 1. Summary Results from New Home Quality Study

Defect Severity	Homes w/ Defect	Average Defects Per Home
Priority	95%	3.8
Concerns	83%	2.2
Worth Noting	75%	1.6
Total		7.6

Bashford (2004) reviewed the 2001 fiscal year Securities and Exchange Commission (SEC) filings for all 23 publicly traded U.S. homebuilders. These large production homebuilders completed and sold 193,515 homes with a sales value of $43.78 billion, for an average sales price of $226,250. These homes represent over 20% of all U.S. home production in 2001, in both sales count and sales value. At the close of the 2001 fiscal year these companies had 81,011 houses under construction, with a stated value of $13.93 billion, a turns rate of 2.4 annual completions to work in process. Using Little's Law (Hopp and Spearman, 2001), the estimated average construction cycle time is 152 days. This estimate is consistent with the average cycle time actually observed for new homes built in Chandler, Arizona during the first six months of 2001 (Bashford 2004). This lengthy construction cycle and the resulting work in process are largely due to non-productive time during the construction process. A multi-year study of on-site home building operations in the Phoenix metropolitan area found that actual construction operations consumed 25 to 40% of available working time (8 hours per day, 5 days per week) (AzPath, 2001). Houses sit idle over 50% of the available work time. These findings are important, both to U.S. homebuilders who tie up over $68 billion in working capital (extrapolated to include all U.S. builders) and to homebuyers who must wait five months for a new home and pay the price for builder delays.

Laquatra and Pierce (2004) summarize results from an empirical examination of construction waste. The methodology included an on-site waste audit of a 1,894 square feet single family home under construction in upstate New York. The audit consisted of weighing, measuring and cataloging every item of debris produced. The audit revealed that packaging and materials debris included 1,788 pounds of gypsum board scraps and over 1,400 pounds of wood scraps. The total weight of all waste materials was 4,642 pounds (2.3 tons). Gypsum, wood and cardboard waste made up almost 75% of total debris by weight. That figure was compared with seven other waste audits that have been conducted around the country and found to be consistent. The issues of reducing and recycling construction waste are important for both environmental sustainability and housing affordability. Environmental aspects are clear: landfill space is becoming more limited; faulty landfills pollute air, earth, and water; and illegal dumping of construction waste is increasing. From the affordability perspective, NAHB has demonstrated that builders pay twice for construction materials that could be recycled but end up in landfills: payment is made when the materials are purchased and fees are assessed when the materials are dumped (Yost and Lund, 1996). These costs are then passed on to homebuyers in the form of increased house prices.

Kendall (2004) described a fundamental tension between homebuyers and builders – homebuyers are demanding customized houses (market pull) while builders are unable/unwilling to deliver, at least at reasonable prices. Builders know that homebuyers prefer to change standard floor plans, components, equipment and finishes. However, builders are understandably reluctant to offer choices because they fear that customization will lower profits - the true cost of customization cannot always be passed to the homebuyer. Builder pricing is typically based on fixed floor plans, quantities and specifications, making it difficult to precisely estimate the cost of variations or changes. At the same time, changes can disrupt the entire estimating, production, delivery and management process, making it even more difficult to manage to manage homebuilding effectively. Therefore, if builders are willing to allow homebuyers to customize, they will usually ask for much higher prices to cover uncertainties. Kendall emphasized that the competitive environment in the local marketplace heavily influences the builder's ability to dictate level and the price of customization.

The operational performance findings in the research cited above are from site-built homebuilding. Comparable findings are available for industrialized housing manufacturers. Modular manufacturers report that 2-7% of their sales is lost to service costs. However, this does not represent the full cost of quality. Factory studies have shown that at least 7% of all factory labor hours are spent on rework (Mullens 1998). Drywall finishing is the leading cause of rework. Rework consumes 44% of all drywall finishing labor. Work measurement studies performed to assess the productivity of modular manufacturers have shown that delays consume 10-15% of labor and perhaps substantially more (Mullens 2004). This does not include time worked at reduced productivity levels while waiting for problems to be resolved. To compensate for these delays and to maintain schedule, manufacturers work overtime at a 50% labor premium. Still, these delays constrict plant capacity.

Housing researchers have not only measured the operational performance of homebuilders, they have explored a wide range of innovative approaches to improve performance. Caldeira (1997) describes the National Housing Quality Program, launched in 1993 by the NAHB Research Center. The objective was to introduce the concepts of the quality revolution to the homebuilding industry. A key element of the program is the National Housing Quality Award (Diez 1997), patterned after the Malcolm Baldrige National Quality Award. While some homebuilders have gained significant benefit from the program (Nedegaard 1997), the concepts have not been universally accepted by homebuilders. Elshennawy, Mullens and Nahmens (2002) report that the modular industry has been reluctant to embrace the broad elements of quality management and describe how a continuous improvement-based quality management system might be implemented.

Many innovative approaches to improve homebuilding performance originated with the Toyota Production System (Ohno 1988) and the philosophy of lean production (Womack and Jones 1996). Lean production is based on five fundamental principles: 1) identify what the customer values, 2) identify the value stream (the steps necessary to create value for the customer) and challenge all wasted steps, 3) produce the product when the customer wants it and, once started, keep the product flowing continuously through the value stream, 4) introduce *pull* between all steps where continuous flow is impossible, and 5) manage toward perfection. Koskela (1993) used lean production principles to derive the philosophy of lean construction (LC). According to the Lean Construction Institute (LCI) lean construction is a production management-based philosophy emphasizing the need to simultaneously design a facility and its production process while minimizing waste and maximizing value to owners throughout the project phases [including the post-construction phase] by improving performance at the total project level, using a conformance-based vs. a deviation-based performance control strategy, and improving the reliability of work flow among project participants (Howell 1999). Stated succinctly, lean construction forces the explicit consideration of value management and work flow in addition to the traditional construction management focus on transformation management, i.e., transferring materials into building objects (Abdelhamid 2004).

Lean construction research has focused on eliminating waste and variability (Abdelhamid 2004). Ohno (1988) named seven sources of waste: 1) over-production - producing more than required by customers; 2) inventory - holding or purchasing unnecessary raw materials, work-in-process or finished goods inventory; 3) transportation - multiple handling, delay in material handling, unnecessary handling; 4) waiting - time delays, idle time; 5) motion - actions of people or equipment that do not add value to the product; 6) over processing - unnecessary processing steps or work elements; 7) correction - producing a part that is scrapped or requires rework. Ballard and Howell (1994) state that achieving reliable workflow is possible only when sources of variability are controlled. The damaging effects of variability on dependent production processes were formally introduced by Goldratt (1992) and later addressed in the construction context by Tommelein, Riley and Howell (1999). Common sources of construction variability include late delivery of material and equipment, design errors, change orders, equipment breakdowns, tool malfunctions, improper crew utilization, labor strikes, environmental effects, and poorly designed production systems. In new home construction, customization is also a significant source of variability.

Planning and scheduling construction activities has been a major focus of homebuilding research. Ballard and Howell (1994) identify the quality of weekly work crew assignments as a key driver of workflow, with quality assignments shielding downstream production crews from work flow uncertainty. Ballard and Howell (1998) suggest that remaining workflow variability can be mitigated through the use of plan buffers, surge piles and flexible capacity. Arditi et al (2001) describe the use of linear scheduling methods and line of balance techniques for planning and controlling highly repetitive construction projects. The strategy is to balance work teams to produce completed units at approximately the same rate. Activities with large work content may require more than one crew to balance, while activities with low work content may not require a full-time crew. Arditi presents a model to optimize resource constraints (number of crews) to meet given delivery deadlines. El-Rayes et al (2002) develop an object-oriented model that can generate efficient schedules for repetitive housing construction. Bashford et al (2002) discuss the use of 'even flow' workflow-leveling to reduce variability in workflow for trade subcontractors. Responding to large month-to-month variability observed in housing starts, 'even flow' attempts to provide a uniform number of starts throughout the life of a multi-house project. In general, the housing industry has found these methods unsatisfactory for production control on a large scale involving numerous independent subcontractors. Mullens and Kelley (2004) show how lean scheduling concepts such as continuous flow and single piece production can be adapted to reduce on-site construction cycle time for modular homebuilders by as much as 50%. Construction worker fatigue (Abdelhamid and Everett 2002) and accidents (Howell et al. 2003) can disrupt schedules as well as have great human cost.

Hastak and Syal (2004) and Mullens (2004) explore the use of lean production principles in the HUD Code and modular housing factories respectively. Both forms of industrialized housing production bear a striking resemblance to site-built housing construction, with several important differences: 1) they take place inside a factory on a moving line and 2) their construction crews are a dedicated resource and the "parade of trades" (Tommelein, Riley and Howell 1999) happens much quicker. As a result, factory production is much more vulnerable to process variability, and production bottlenecks are cited as a critical challenge for both HUD Code and modular production. HUD Code research has focused on investigating improved factory designs, including layouts, modern equipment, optimized line balancing and the use of simulation as a modeling tool for evaluating factory design enhancements. Modular research efforts have addressed these same topics. Recognizing the modular industry's trend to provide greater customization, research is also investigating the real-time phenomenon of floating bottlenecks - bottlenecks that shift between operations depending on product mix. It is believed that floating bottlenecks are a root cause of operational problems (productivity, capacity and quality) in the modular factory.

Mullens and Toleti (1996) investigate alternative sequencing strategies in an automated wood frame panelizing line. After developing a scheduling strategy to capitalize on the specific configuration of the automated line, computer simulation was used to verify the expected improvement. Subsequent implementation yielded 7-10% increase in line capacity, with no increase in labor. Mullens and Nahmens (2004) explore the application of lean principles to the production of precast concrete panels for residential construction. To assure a continuous work flow, researchers recommended formalizing supervisory responsibilities, eliminating language barriers, standardizing worker assignments, establishing off-line sub-assembly operations and improving reliability of component flow to the forming beds. Implementation results demonstrated a 50% increase in labor productivity and a 25% reduction in cycle time. Armacost et al. (2001) develop an effective heuristic algorithm to schedule truss production by considering the problem of minimizing makespan on unrelated parallel machines with sequence-dependent setup times and machine eligibility restrictions.

Material waste on the construction site is significant. Drywall waste alone can average one ton per house (Laquatra 2004). Yost and Lund (1996) found that while 80 percent of the waste stream at a residential construction site may be recycled, various obstacles prevent that potential from being realized. For example, even though drywall waste can be recycled into new drywall product or treated as a soil amendment, the low cost of new drywall and the additives used to produce moisture resistant and fire resistant drywall products make it less desirable. Lacking viable recycling options, landfilling, incineration and ocean dumping have also been explored (Laquatra 2004).

Advanced technologies have been a popular topic of homebuilding research. Bernhold (2004) has investigated the use of an Integrated Wireless Site (IWS). A prototype IWS was tested for a building contractor on the North Carolina State campus, providing value added information to the owner/user, sub-contractors, the engineer/architect and inspectors. Field test results show promise in improving communication between contractors, suppliers, and homeowners. Wakefield, Obrien and Beliveau (2001) explored information integration in order to see how information exchanges, relationships, and mechanisms shaped construction operations. It includes a record and analysis of the information flows and breaks on construction sites, as well as recommendations for overcoming these breaks. In a follow up study (Obrien, Wakefield and Beliveau 2002) the researchers explored the impact of these information breaks on actual workflow. A variety of technical and managerial approaches were studied that could lead to more rapid construction production, with better planning and coordination, and with more efficient material and labor use. Jeong (2003) performed a macro analysis of the current supply chain for the HUD Code industry and recommended broad adoption of information technologies such as Enterprise Resource Planning (ERP). Broadway and Mullens (2004) describe an approach for collecting, analyzing, reporting and using labor data to manage shop floor operations for housing manufacturers. The approach couples barcode scanning and wireless communications technologies with custom software, enabling employees to easily record their activities on a real-time basis. Web-based software provides analysis and reporting of production performance from either a real-time or historical perspective. Lessons learned from early implementation efforts are summarized, including both technical and organizational concerns affecting data accuracy and user acceptance. At a strategic level, Bashford (2004) examines why there have been few changes in residential construction practices, even while there have been numerous new products and processes developed that could bring significant improvement. He observes that a major barrier is the fact that virtually all construction work is performed by independent trade contractors who seek to protect their individual interests. Improvements in the work practices of one trade contractor can have undesirable ripple effects upon other contractors who receive no benefit from the improvements. He argues that completely new supply chains must eventually be developed in order to accommodate systems that affect more than one trade.

Wiezel (2004) proposes a long-term vision for integrated design and construction of housing. He envisions that: 1) the new homebuyer will be able to take a virtual walk through a proposed home design, not only visualizing the design, but physically sensing objects such as walls and stairs, 2) the optimal building technology will be automatically selected, 3) all planning documents will be automatically created and forwarded to approval agencies, vendors and sub-contractors, 4) factory-built components will be automatically manufactured and shipped, 5) the house will be assembled on site by workers equipped with automated devices for visualization, positioning and strength enhancing, and 6) building documentation – as-builts, controls, and maintenance procedures – will be provided digitally to the buyer. Wiezel states that a critical component of the vision is a formal model capable of linking home design to construction processes, similar to those used in manufacturing for automated production planning systems. More specifically, building objects must be linked to construction activities and activities linked to specific construction worker skills. Oztemir (2003) has contributed to this effort by developing a method to separate any construction activity into tasks, sub-tasks and movements along with an approach for modeling and measuring the skills required by each activity. To complete the theoretical infrastructure for process modeling, Wiezel suggests the development of a taxonomy of construction methods to organize construction activities and a construction algebra to allow activity reasoning.

Kendall and Teicher (1999) draw on Habraken's (1972) innovative 'shell-infill' concept to provide a new dimension to consumer-oriented 'just in time' housing production. This 'open building' approach is a set of principles and methods that divide the total process and product of house construction into two decision levels: shell and infill (Kendall 2004). The shell is the result of design decisions specific to the site, constrained by local regulations and conventions, geo-technical and environmental conditions. Generally, the shell includes the foundations, building structure and envelope, stairs, and main mechanical/electrical/plumbing (MEP) systems. The infill is the set of design decisions and products – decoupled from the shell and "kitted" for delivery and installation by multi-skilled crews - needed to make a shell habitable and less difficult to alter later without disturbing the shell. This approach makes it possible for the developer to offer, in a particular shell design, a variety of interior layouts, equipment and finish choices. This two step strategy of home design and construction allows a developer to defer specific unit decisions (and costs) until the point of sale or lease without risk. It also enables individual buyers to act on their preferences and budgets, initially and over time.

Future Research Directions

Although diverse, the homebuilding literature is consistent in its message: housing - in its broadest sense 'a product and a process that delivers a bundle of services to individuals and communities' - has great potential for enhanced quality, timeliness, efficiency, variety and sustainability. However, challenging research issues must be addressed before this great potential can be harnessed. In summary, metrics, methods and tools must be developed to achieve the desired improvements in homebuilding performance. We believe that this research can be organized in the following areas: 1) enhancing demand side pressure for quality, 2) developing fundamental construction theory, 3) coordinating the disaggregated supply chain, 4) developing shell and infill processes and technologies, 5) balancing off-site and on-site production, and 6) innovation in safety, quality, scheduling and cost management systems. This section considers these topics in greater detail.

Enhancing Demand Side Pressure for Quality:

In the current over-heated housing market where demand is fueled by low interest rates, there is little motivation for a builder to construct high quality houses. Homebuyers care little about quality beyond the cosmetic and high demand pressures the builder and subcontractors to hurry. It will be difficult for a builder, especially a builder in this market, to make a strong commitment to quality without strong pressure from other primary stakeholders in housing: homebuyers, mortgage and banking institutions, and insurance providers. But before stakeholders demand quality, they must be able to recognize quality and appreciate the value of quality construction. Therefore, early research efforts should include benchmarking current stakeholder understanding of housing quality. An important element of this research will be benchmarking incentive systems used in the mortgage and insurance industries to recognize long term value, durability and adaptability of the housing stock.

Before educating stakeholders, additional research will be required to establish quality indicators. Indicators must not only be linked to housing performance (safety, durability, comfort, appearance, maintainability), but be readily discernable by homebuyers so they can distinguish between builders. Indicators will likely include housing specifications, materials, components, and workmanship. Likely sources for quality indicators include NAHB publications, the J.D. Power and Associates homebuyer survey, and home inspection check lists.

The research must clearly document the relationship of each quality indicator to housing performance and explore the relative importance of different indicators.

Developing Fundamental Construction Theory:

Better understanding of the elemental structure and dynamics of home construction is necessary if the homebuilding process is to be rationalized. Research in this area is likely to facilitate the development of computer automated construction process planning methodologies and tools (Wiezel 2004) and eventually enable improved homebuilding automation. The model envisioned would link home design to construction processes – first linking building objects to construction activities and then linking activities to specific construction worker skills. A limitation of existing construction process representations is the use of a macro representation of activities. Even in the most advanced representations, activities cannot be broken down into operations and the skill levels of workers are not accounted for. A model that would support optimization of the homebuilding process will not only have to represent each task of each activity, but also reason about the skills required to perform the tasks. Oztemir (2003) has contributed to this effort by developing a method to separate any construction activity into tasks, sub-tasks and movements along with an approach for modeling and measuring the skills required for each activity. While the method allows a complete representation of all tasks in an activity, a taxonomy of construction methods is still needed to allow formalizing the search for an appropriate construction method in the presence of given labor skills. The taxonomy will also allow the evaluation of new construction methods and even the discovery of new methods that may be appropriate for the available skill pool and equipment.

While progress has been reported in modeling construction objects and the definition of a construction workspace ontology for activities, at least one critical element is missing. Termed 'construction algebra' (Wiezel 2004), it consists of a minimal set of relationships between objects and tasks, as well as the rules to operate with those relationships. The relationships allow operations sequencing to be automated and form the base for construction process optimization. Once detailed, tasks can be generated in concordance with available skills and construction methods and automatically aggregated into activities, optimizing the whole construction process for time, cost or safety.

Coordinating the Disaggregated Supply Chain:

The homebuilding supply chain is unusually large, complex, and dynamic. Product suppliers provide a wide range of stock materials (e.g., insulation, roofing) and custom components (e.g., trusses, cabinets), with delivery times ranging from hours to months. Some materials are purchased speculatively to hedge against market swings (e.g., dimensional lumber, steel framing components). Managing the product side of the supply chain is non-trivial, ensuring specified materials are on-site when needed (and not before), staged in the proper location, protected from theft and damage, and provided at the overall best value to the homebuyer. However, it is the services side of the supply chain that often presents the greatest challenge. Almost no homebuilders who build more than 50 homes per month actually perform any construction work (Bashford 2002). Instead, they rely on 25-30 independent trade contractors who actually build the house. Difficulties arise in coordinating the numerous independent contractors with a series of complicating factors: multiplicity of interactions between contractors, workflow variability in a long, sequential production system, and repetition of this problem across multiple homes simultaneously under construction.

Research is needed to better manage the homebuilding supply chain, increasing value for the homebuyer. Specific research topics might include: 1) how does the structure of the housing industry affect supply chain management, 2) what are current best practices in construction supply chain management, 3) can we simplify the supply chain by creating value-added partnerships or simply adding additional value at a supplier, 4) can we increase cooperation or better integrate suppliers, perhaps through technology such as the IWS (Bernhold 2004) or the "kitted" infill system approach suggested by Kendall (2004), 5) how do we simultaneously accommodate customization while standardizing to reduce process variability, 6) how can we structure the supply chain to minimize the impact of replacing a material supplier or trade contractor, and 7) how can Just in Time (JIT) concepts enhance homebuilding supply chain performance (e.g., material delivery, shell/infill concepts for JIT design decision-making).

Developing Shell and Infill Processes and Technologies:

Open building, a set of principles and methods that divide the total process and product of house construction into two decision levels, shell (the more public decisions) and infill (the more individual homebuyer decisions, is well known internationally. Known as base building and tenant fit-out, the open building approach is widely used in office and commercial buildings worldwide. Although housing projects in the Netherlands, Finland, and Japan have used open building concepts, U.S. homebuilders have not embraced open building. Research is needed to explore the technical, business, and regulatory challenges to shell and infill approaches.

Open building requires that interdependencies between the two major subsystems – shell and infill - are decoupled or reduced to a minimum (Kendall 2004). Those interdependencies that remain must be well organized with explicit standards for dimensional coordination, positioning and interfaces. This principle also applies to the interdependencies between parts within each subsystem. Research is needed to explore approaches to manage these interdependencies. Building service components (electrical, mechanical, water, wastewater, and telecommunications) and the interdependencies they create with walls, floors and ceilings merit particular research effort. Current wood/steel frame construction methods thread building service components into, under, around, and through the structural frame. This 'entangling' creates excessive interdependencies between system components and their respective trade contractors. Thus, research is needed to disentangle building service systems from the house structural system and from each other (Bashford 2004). Disentangling will not only reduce interface complexity and conflict during construction, but will facilitate factory production of interchangeable infill components oriented to the consumer market in the same way as other consumer products. Concurrent with these research efforts to manage interdependencies and disentangle services, impacts on the construction process should be assessed, with a view towards using the new systems to shorten the current lengthy serial construction process, improve quality and facilitate ongoing retrofits to meet the changing needs of homeowners.

Research is also needed to explore supply chain innovations necessary to support shell and infill homebuilding strategies. Likely opportunities include product bundling and kitting to support infill construction, factory production of larger, standardized, interchangeable infill components and the use of multi-skilled infill installation teams. Finally, research is needed to explore the regulatory and trade impacts of shell and infill homebuilding.

Balancing Off-site and On-site Production:

Mullens (2004) provides an idyllic vision for the industrialized housing factory of the future.

> *The factory will produce high quality custom homes for all homebuyers, from entry level through luxury. The factory will provide a productive and safe environment that will offer excellent value and timely delivery for the homebuyer, a safe and rewarding career for employees and a profitable investment for owners. Ample capacity will be provided to accommodate forecasted short-term growth. Factory design will be modular and flexible to facilitate expansion to accommodate more rapid or longer-term growth. Materials will arrive in the factory just in time to support production and be staged close to the point of use on the line. Mechanization/automation will be provided for both material handling and manufacturing processes when justified to eliminate injuries, minimize excessive physical exertion, assure capacity and boost productivity. Production documentation will be timely and accurate. Employees will know the status of any order, recognize the restrictions at any workstation or work group, and be able to react so that schedule and customer demands can be profitably met. As a result, rework will be minimal and production flow will be smooth and synchronous with demand. Employee work groups will be actively engaged in continuous improvement and will share in the resulting profits.*

Smooth production flow, leading to excellence in safety, quality, capacity and productivity, is at the core of the vision. Research addressing the following key drivers of production flow is needed: module design, process and material handling technology, factory configuration, and shop floor control. Industrialized housing manufacturers seek new home designs, materials, equipment and systems that are engineered specifically for factory production and that provide strategic advantage over site builders. For example, producing and shipping roofs separately will enhance design flexibility by allowing higher ceilings and taller roof lines, while smoothing flow by eliminating a critical line dependency on the roof assembly workstation. A shell and infill approach to interior finishing would outsource most of the difficult interior finishing activities to specialized first tier suppliers, allowing increased capacity in housing factories and increased customization to better meet specific homebuyer needs.

Factory configuration plays an important role in production flow. While a variety of configuration innovations have been advanced (Hastak and Syal 2004, Mullens 2004), assessing their impact is non-trivial. Assessment quickly becomes intractable when variability caused by randomness, module design, and shared resources are considered. Research should address systematic strategies for developing and evaluating configuration options. While analytical heuristics may be useful, simulation tools are likely to be essential.

Innovations in information technology are necessary if production flows are to be effectively planned and managed. Effective control begins with the acquisition of data. Traditional approaches to collecting housing process times are cost prohibitive and unreliable – current data are simply not available. One answer may lie in real time data collection tools such as automatic identification (e.g., bar code scanning, radio frequency identification). Significant challenges lie in developing ubiquitous, unobtrusive systems that work in dirty, rough, open (even outdoor) environments. Using these tools on a perpetual basis can provide the data needed for real time shop floor control and longer-term continuous improvement. Raw data, however, provides little actual management information. Predictive labor models, using regression or neural nets, are needed for planning and control. Real time shop floor control will require the development of decision support systems that assist in module scheduling and labor assignment. Technologies are likely to include optimization, simulation, and visualization tools for generating and evaluating alternatives.

Future research should also be directed towards streamlining information flow to improve supply chain performance. Timely and accurate sharing of information will help all parties accommodate customer needs more quickly and at lower total cost. The following research is needed: defining current practices of information flows in the supply chain and identifying typical systems, identifying information technology (IT) tools or advanced systems already applied in other industries, identifying information bottlenecks using supply chain analysis, and implementing selected IT tools or systems in industrialized housing and assessing their effectiveness in the industry.

Homebuilders that use industrialized housing components routinely add site-built structures to meet the needs of specific projects. For example, factory-built modules are typically supplemented with site-built garages. Sometimes modules are topped with site-built or factory-panelized roofs to accommodate unusually complex rooflines. Research efforts are needed to explore the synergies between various industrialized housing technologies and to pursue promising hybrid approaches.

Innovations in Safety, Quality, Scheduling and Cost Management Systems:

Directed research studies targeting key operational performance measures are needed. For example, continuing research is needed to reduce waste construction material and increase recycling. Research involving community-based programs that link builders with local collection and recycling groups could form the basis for large-scale demonstration efforts (Laquatra 2004). Further research on economic and environmental benefits of these efforts might encourage builders to adopt sound waste management practices as a routine part of construction.

Continuing research on project scheduling is needed to reduce lengthy construction cycle times (Abdelhamid 2004). The use of lean construction principles – single home production, continuous flow, Last Planner? and Six-Sigma - for planning site construction operations might be examined using analytical and simulation models and then demonstrated through a small scale demonstration project. Related research is needed to attack all forms of homebuilding waste. Homebuilding activities might be observed to identify and quantify the seven types of waste targeted by lean construction. Improvement opportunities might then be identified and implemented using a Kaizen blitz improvement process.

Work physiology research has shown that physically demanding work leads to physical fatigue, which can lead to inattentiveness, poor judgment, accidents, and injuries (Abdelhamid 2004). Continued research is needed to explore the physical demands of homebuilding operations using current ergonomic principles. The research might also address strategies to reduce fatigue by changing work methods, investing in automated tools and equipment, providing work-rest cycles, or simply adjusting management expectations of workers.

Expanded operational use of advanced information technologies should also be explored. The Integrated Wireless Site (Bernhold 2004) and the Status Tracking and Control System (Broadway and Mullens 2004) are prototype wireless networks for the homebuilder that can also provide value added information to the owner/user, sub-contractors, engineer/architect, and inspectors.

Cross Cutting Impacts:

The crosscutting impacts of the recommended research topics on the other broad topical areas (2) structural design and materials, 3) building enclosures, energy and indoor air quality, 4) housing technology, community and the economy, and 5) systems interactions and "whole house" approach) are shown in Table 2. Primary research disciplines will likely include architecture, civil engineering, construction management, and industrial engineering. Other disciplines (Table 2) may also make valuable contributions for selected research topics.

Table 2. Crosscutting Impacts

Research Topics: Construction Mgmt. and Production	**Other Topical Areas**				**Other Disciplines**	**Notes**
	2	**3**	**4**	**5**		
Enhancing Pressure for Quality			X		Marketing	
Developing Construction Theory						
Coordinating Supply Chain					Management	
Shell & Infill				X		
Off-site vs. On-site Production	X			X		
Innovations: Safety, Quality, etc.					Computer Science	

Justification

The proposed housing research is motivated by the well-documented need to improve homebuilding operations in all key performance metrics: quality, timeliness, efficiency, variety and sustainability. No amount of research in structural design, materials, building enclosures, energy, indoor air quality, systems interactions and 'whole house' design will provide meaningful improvement if homebuilders lack the capability or willingness to deliver it. The proposed research program has the ambitious goal of developing the core concepts, process methods/tools, and perhaps even the marketable products that homebuilders need to deliver the right technical product at the right business cost, thus assuring that the nation's need for housing and the industry's need for profitability are effectively met.

Looking beyond the urgent societal and economic needs, the proposed housing research has a solid scientific foundation. The fundamental research question is formidable, so much so that it must be addressed in multiple dimensions. Significant research streams are already underway. State-of-the-art findings are published and available to the research community to build upon. Many innovative concepts are being generated from this research and they require further investigation. A fundamental part of these investigations will involve establishing the technical and commercial feasibility of innovative concepts.

Summary

There is great potential for enhancing the quality, timeliness, efficiency and variety of new housing in America, benefiting American homeowners, homebuilders and society at large. However, challenging research issues must be addressed before this great potential can be harnessed. In summary, metrics, methods and tools must be developed to achieve the desired improvements in homebuilding performance. As evidenced by the active participation of leading researchers at this workshop, the U.S. academic community stands ready to meet our nation's critical housing research needs.

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