quality between housing producers, buyers, and government;

- lack of agreement between product manufacturers, housing producers, buyers, and government on durability and responsibility for the durability of a house.

The inability of the housing construction and research communities to rapidly document and disseminate critical (endangering life, health, investment return) interactions between subsystems, materials, climate, design, and production practices combined with higher annual production volumes increases the likelihood that a particularly low-performing combination will be implemented by a home builder. There are too many products, used in too many ways, in too many locations to continue design and production practices that assume since this new way is similar to the old way, the new way will work out fine. Broader testing protocols testing products and practices in construction assemblies in climatic conditions found in the United States are needed to help homebuilders avoid problems caused by poorly performing materials and practices.

Current Efforts at Performance Integration

Government agencies are active in promoting subsystem performance. Methods for improving indoor air quality and improving health through low-toxicity materials are being promoted through HUD's "Healthy Homes" program. Energy subsystem performance-based design is being advanced through programs such as "Energy Star" from the U.S. Environmental Protection Agency and the U.S. Department of Energy. A key tool in this program is "Energy 10," a user-friendly energy-modeling system enabling rapid evaluation of the performance of design and construction alternatives. Postdisaster publications from the Federal Emergency Management Agency actively promote performance upgrades based on the nature of the subsystem failure.

The residential construction industry is active on a number of performance fronts, with significant research on cost reduction of framing being most notable. Structural subsystem performance-based design for residential construction has roots extending from the OVE methods previously discussed to the current initiative of NAHBRC titled "Housing Affordability through Design Engineering" (HATDE), supported by HUD. Both the OVE and HATDE apply contemporary engineering principles to the structural design of the wood frame house.

Professional and scientific standards institutes are also active in the discussion of residential performance. The National Institute of Building Sciences subcommittee Building Environment and Thermal Envelope Council (BETEC) has facilitated the national and international discussion of building envelope performance and impact on air quality. Initial steps towards the development of design methods and tools for performance integration–based design are in the early stages of development with the American Society for Testing and Materials.

Home buyers represent another party that holds strong performance expectations in addition to minimums established by building regulation. Home buyers across market segments have widely varying expectations for affordability, investment return, acoustical performance, durability, maintenance, and security that need to be regularly surveyed and applied to performance integration methods.

Approaches to Performance Integration

Performance integration includes

- minimizing adverse loading of one subsystem by another,
- minimizing operating costs over the life of the loan,
- minimizing carbon dioxide contributed to the environment by the construction and operation,
- optimizing subsystems towards total house behavior rather than discrete subsystem behavior,
- protecting the indoor environmental qualities of the house (acoustic, air quality),
- protecting inhabitants during extreme service conditions, and
- facilitating the full use of the house by users with disabilities.

"Performance" definitions vary according to geographic location, market segment, and the person doing the defining. Building regulations establish minimum levels of performance for thermal, life safety, ventilation, lighting, plumbing, and structural systems. For the purposes of this study, construction performance must be considered from the following perspectives, which vary across large regions of the country:

- structural loading,
- thermal/moisture protection,
- environmental impact,
- economic return, and
- production rate—constructability.

The design or optimization hierarchy may vary not from state to state, but by markets from region to region. For example, in Minot, North Dakota, the hierarchy may be thermal/moisture protection, economic return, structural loading, production rate, and environmental impact, while on the Outer Banks of North Carolina the hierarchy may be structure, economic return, thermal/moisture protection, environmental impact, production rate. The hierarchies of which system makes concessions to which system need to be based on economic, climatic, market, labor, and disaster threats unique to each region. These performance hierarchies would be considered primary in the performance design and analysis. Additional and more localized performance perspectives may also include acoustic performance (airport or interstate locations), soil capability, and pest resistance.

A next step for the development of performance integration methods is to assemble an inventory of performance standards to identify conflicting measures and subsystems or performance measures left undefined at present. This inventory should include the following:

- building regulation performance minimums,
- home builder measures of performance across market segments,
- home buyer expectations across market segments,
- standards institutes performance measures,
- government agencies expectations for performance,
- standards for thermal loading by lighting and appliances,
- standards for thermal loading by envelope,
- standards for moisture loading by vapor/cooling ducts within structural assemblies,

- standards for moisture loading of structural assemblies,
- standards for volatile organic compounds, radon, and mold/mildew levels in air,
- standards for acoustic levels from indoor sources,
- standards for interior acoustic intrusion from outdoor sources,
- standards for structural loading by envelope (roof vent/snow load),
- standards for structural loading by interior furnishings,
- standards for smoke and fire contribution by house components,
- standards for smoke and fire contribution by house furnishings,
- standards for accessibility.

Performance levels for the above are held at minimum levels by regulatory agencies, professional and trade associations, and code writing bodies. Minimum performance levels are usually the result of negotiations during the process of developing standards and codes and are adjusted as new knowledge is acquired and the political will of constituents brings this knowledge to bear on existing standards.

Tools commonly used in research institutions for analysis of housing subsystem behavior include sophisticated energy and structural modelers and modelers of lighting analysis, air flow, vapor transmission, ergonomics, fire, carbon debt, acoustics, security, and accessibility. Housing designers and producers commonly use structural analysis tools, occasionally use thermal analysis tools, but use other performance analysis tools infrequently, possibly due to poor interface design and the need to reenter data about the design (the software cannot pick up data from CAD drawings).

Industries such as aerospace, automotive, and chemical production commonly use virtual prototyping tools to understand the performance impacts of design and construction decisions. Virtual prototyping enables structural, environmental, extreme service, ergonomic, and accessibility analysis prior to the production of a physical prototype, saving considerable cost in both the short term (reductions in the number of prototypes constructed) and the long term (losses related to product liability). Current generations of these tools are beyond the investment possible and expertise available within the housing design and construction communities. Object-oriented CAD systems are taking the first steps towards virtual prototyping by including databases and intelligent objects as part of the system. These same systems will make sharing data with more sophisticated subsystem analysis software simpler. This advance, coupled with a user-friendly interface, could make whole-house performance analysis as cost-effective and straightforward as structural analysis is today.

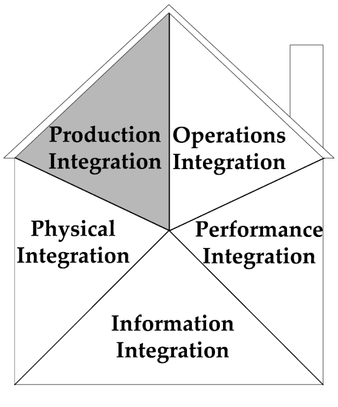

Figure 3.5: Production integration

PRODUCTION INTEGRATION

Production integration, conducting the many operations as one (or fewer), is relatively more advanced among the five approaches to integration (information, physical, performance, production, operations) in terms of adaptation of industrial processes. Production integration continues to be developed along four primary fronts:

- design for rapid construction,
- planning and coordination of the stages of construction through construction management principles,

- use of materials that incorporate the performance of many discrete parts of an assembly into one material (structural insulated panel systems, insulated and precast concrete foundation systems), and
- panelization and the use of pre-manufactured components to speed site installation.

The application of industrial product design, materials handling, project management, and production planning techniques is not a recent phenomenon in the residential construction industry. The late 1890s and early 1920s saw an explosion of "precut" house kits. Manufacturers of these kits precut, marked, and bundled materials to ensure material quality and size, minimize waste, maximize productivity, and reduce costs. The Gordon Van Tine company promoted its "ready-cut" line of houses as being able to be "dried-in" in less than seven days (Tine 1923). By 1919 the company was offering "turnkey" services in the greater Moline, Illinois, area.

As early as 1947, the designers and builders of the first Levittown development had extended a vision of the construction site as "the outdoor factory" (Hoefstra University 1994). Model house plans were designed with production efficiency in mind. Prototype construction was carefully documented using time-and-motion methods similar to those used in the automotive industry to refine the design for enhanced production rates. The production process was divided into 26 main processes, each having subsequent materials-handling and installation breakdowns. Even landscape materials were part of the industrial thinking, with layout, excavation, soil enrichment, tree delivery, soil replacement, and tree staking handled by separate crews that literally ran across Levittown completing their work. Independent subcontractors (who thought of themselves as Levitt employees) were paid on a piecework basis to encourage productivity. Supply chain obstacles were overcome by purchasing lumber mills and nail production plants. Transportation limitations were overcome by installing a railroad siding for the project, with product purchases scaled to rail-car quantities. Over the four-year build-out of Levittown, 17,447 homes were constructed and sold for as little as $7,990 ($66,300 in 1999 dollars) with a completion rate of 25 to 30 homes per day.

The major difference between the Levitt model and a large percentage of the homebuilder industry is enterprise integration. As a homebuilder, Levitt had in-house departments for land acquisition, design, engineering, construction management, finance, and legal. With subcontractors being paid on a piecework basis and seeing themselves as Levitt employees, communications, process, intent, and quality were easily managed.

Today, planning techniques such as linear scheduling enable a builder to graph ideal start and finish times for each stage of the work and use the same graph to monitor progress in each of the work units. Linear scheduling enables a builder to see problems approaching in time. The builder can either add labor and materials to address the problem or shift the ideal start/finish times for all following work units to accept the delay (Ragolia et al. 1998). When the actual graph of the progress crosses to the left of the ideal production rate line, the builder knows that action to mitigate or acceptance of the delay and rescheduling subsequent work operations is necessary.

OPERATIONS INTEGRATION

Operations integration means running the many parts as one. During performance integration of design and engineering, interactions between the static systems (envelope, structure, insulation) and dynamic systems (lighting, HVAC, power, irrigation, security) are carefully choreographed to provide the highest performance in terms of affordability and durability. The integration of information carries these design decisions—along with physical integration decisions—into the production stage, where subsystems are fabricated, assembled, and installed.

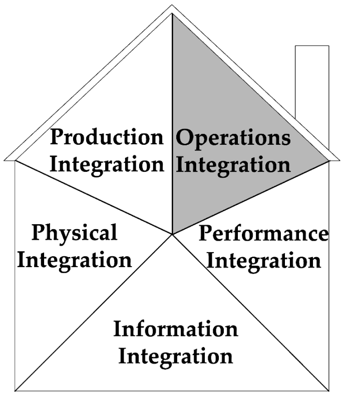

Figure 3.6: Operations integration

Traditionally, design and construction responsibilities stop when the homeowner is handed the keys and a package of manuals covering the care and maintenance of the subsystems and appliances. Some of the more comprehensive packages have maintenance schedules helping the homeowner remember to change furnace filters, purge the hot water heater, lubricate moving parts, open and close crawl space vents, change the washing machine hoses, and vacuum under the clothes dryer on a regular basis. Program settings for setback thermostats, security systems, and irrigation systems might be written on the back of the manual, should the owner be fortunate enough to be able to enter the programming mode.

Today it is possible—and expected in some higher-end market segments—to centralize the control of these subsystems. Home automation systems are becoming more affordable, easier to program, and able to alert the homeowner to complete scheduled maintenance. As home systems and appliances become more numerous, the chances are good that one active system will be operating in conflict with another (e.g., the humidifier causing condensation on window and wall surfaces). More difficult to detect at present, but more important, is the effect these active system conflicts can have on durability and air quality.

Powerline carrier–based systems, also referred to as “X-10,” dominate this growing product market. In the next year, Honeywell Corporation will introduce the “Home Controller,” a home systems operations integrator supporting telephone, home control panel, and World Wide Web interfaces enabling control of appliances, HVAC, telephone, lighting, and security systems. The Home Controller will use electrical wiring as the network backbone, “piggybacking” signals over the electrical current to control devices. This system will also be compatible with Ethernet and CEbus protocols. The system is sold through home improvement centers and computer stores across the United Kingdom. The Home Control system featured in the “future homes” project in Glasgow, Scotland, enables homeowners to remotely control lighting, appliances, and heating and cooling on a timer from a handheld remote or from a home computer. The system is modular, enabling homeowners to upgrade the number of devices controlled or the mode of control as their need and budget allow.

Next steps for these operations integrators will be the development of a whole-house sensor network able to monitor conditions within walls, in attics, and at critical structural connections. This capability will speed assessment of the condition of the structure and insulation and detect environmental conditions within wall/floor/roof assemblies that enhance the development of molds, mildew, fungi, bacteria, and insect pests. Off-the-shelf technologies are currently available to perform many of these functions, but like the operations integrator itself, the cost exceeds perceptions of value in most market segments.

The operations integrator would also include information collected from the production stage on quantities and composition of materials, key subsystem construction, and floor plans, highlighting locations of materials and products which are particularly hazardous or explosive during a fire, post-disaster search and rescue, and recycling of the house and debris at the end of the service life. Properly configured with existing lighting control systems, the operations integrator could also report last known location of occupants to fire or search and rescue personnel.

SYSTEMS INTEGRATION AND HOME BUILDING: CURRENT TECHNOLOGIES

Componentization

Perhaps the most rapidly diffused innovation produced by Operation Breakthrough were roof truss components. These pre-engineered components entered the housing market in the late 1960s and by the middle 1970s were the dominant method for framing gable roofs for single- and multifamily construction. As an engineered truss, these components offered designers longer unsupported spans and offered builders significant timesavings in roof framing and greater dimensional accuracy. The only change to homeowners came in the loss of the attic as a storage and potential expansion space. This disadvantage did not impact the use of roof truss components, as many homebuyers were moving up from a “starter” house. These postwar starter houses frequently were one-story, slab-on-grade construction with a lower roof slope (4:12), which did not offer the storage and expansion possibility, so the builders’ switch to trusses and resulting loss of attic space did not impact the market in a negative way.

The component industry began responding to the market’s call for greater flexibility in roof and ceiling design by offering trusses with small useable attic spaces carved into them, cathedral ceilings, and steeper roof slopes made possible with stacked or piggyback trusses. Due to longer span possibilities and reduced labor costs for routing plumbing and electrical systems, floor trusses are becoming more common in residential construction, including those specially designed to accept ductwork.

Both floor and roof trusses depend on relatively precise field placement of walls and beams for proper bearing. Based on letters and articles in *Woodwords*, the trade journal of the Wood Truss Council of America (WTCA), the cutting of wood trusses on site to accommodate changes in ceiling, plumbing, or mechanical system is an ongoing concern (Hoover 1999). As these plate trusses become more common, plumbers, electricians, and mechanical contractors become more familiar with what can and cannot be cut or drilled. When field modifications are made to the top, bottom, or intermediate chords of the truss, the truss needs to be reengineered, often by the manufacturer of the metal plate connectors, to be certain the repair will perform as well as unmodified trusses (Hutchins 2000).

Failures of the plate truss components are few and are often related to improper field handling, placing, or bracing of the trusses. The industry is concentrating quality improvement efforts on in-plant quality training and on-site training of labor for proper placement and bracing.

Panelization

Panelization is currently practiced as the assembly of rough framing pieces (plates, studs, sheathing) into 8- to 16-foot-long wall panels in factory settings, shipped to the site, and erected. Plumbing, wiring, insulating, and finishing still take place on site. This method enables assembly to be conducted in dry settings, by trained labor, with regular quality control checks.

Construction of wall panels in factory settings is increasing due to challenges of securing enough qualified on-site labor, rising tipping fees for construction scrap, and competitive forces in the production housing market. Some production builders have tied the purchase of wall panels to the purchase of floor and roof trusses, requiring component manufacturers to begin production of wall panels to keep supplying floor and roof trusses (Edwards 1999). Additionally, complete home packages consisting of wall panels and roof and floor trusses are available from major home improvement retailers.

When comparing panelization to on-site framing of walls, the WTCA found that lumber quantity requirements were comparable, but that panelization achieved a 60 percent reduction in time for the framing crew (Wood Truss Council of America 1996). The framing experiment "Framing the American Dream" was conducted at the 1996 National Association of Home Builders convention site. It involved side-by-side construction of stick-built framing (joists, studs, rafters, with plywood and oriented strand board [OSB] sheathing) and component framing (wall panels, floor and roof trusses, with plywood and OSB sheathing) of identical 2,600-square-foot house plans. The results showed the following advantages of using components rather than stick framing:

- savings of 253 man-hours ($4,560 in 1996 dollars)
- savings of 5,300 board feet of lumber ($1,529)
- reduction of construction scrap from 17 to 4 cubic yards (Waste generation related to the construction of wall panels and floor and roof trusses is handled at the component fabrication plant, where small scraps can be used in other components or as fuel for the plant.)
- cost savings of $3,356 (1996$) on labor, material, and tipping fees

Floor and roof truss framing also speeds installation of electrical, plumbing, and ductwork systems, offering additional savings.

PLANNING AND COORDINATION OF CONSTRUCTION THROUGH CONSTRUCTION MANAGEMENT PRINCIPLES

Managing process versus managing production

In the William Jamerson Professor lecture in Blacksburg, Virginia on December 1,1999, Dr. Ron Wakefield noted that the diffusion of construction management methods and software has led some construction managers to focus on managing the process, and not the production (Beliveau and Wakefield 1999), the difference residing primarily in the dialogue that occurs between field crews and designers. In production management, difficulties in assembling the product are fed back to product and process designers to improve the manufacture of the next product. Process man-