which account for the laws of physics when moving, bending, or colliding with other elements in the simulation environment. Simulation programs are commonly used in industry to pre-fit parts and pretest assembly procedures, saving millions of dollars in time and physical prototypes.

For residential construction, a simulation environment can couple the object-oriented model to a process modeling program currently used in industrial applications to determine staging points for materials and components and locations for cranes and lifts. This simulation environment could enable the production builder to view the whole development's progress through a three-dimensional progress chart. This proposed use of the simulation environment for design, production planning, and production progress reporting is based on existing industrial production planning and evaluation tools and will be more cost-effective for the home builder when existing object-oriented, three-dimensional CAD files are imported into the simulator because it will reduce repetition of model construction.

When the people involved in the decision making, design, production scheduling, production, finance, operation, and maintenance of the house have access to the current information about the house, the remaining four conditions of integration, described in the following subsections, will be easier to achieve. For the shift towards the industrialization of the residential construction site, similar broad reconsideration is useful for identifying key knowledge to be developed and key tasks to be undertaken.

PHYSICAL INTEGRATION

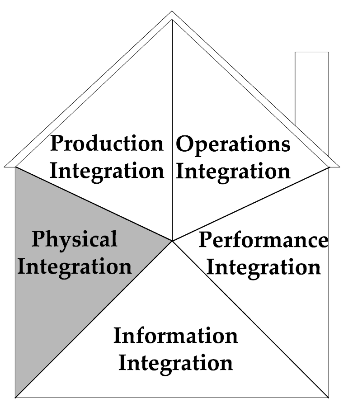

Figure 3.3: Physical integration

Physical integration, making the many parts fit together as one, is the next step towards enabling higher levels of integration. These include production integration (DFA), performance integration (multiple subsystem coordination/optimization), and operations integration (long-term durability and serviceability). With the computing skills on hand in most home builders' offices, information integration—beginning with object-oriented CAD systems—will likely be the key to addressing higher levels of physical integration. Performance gains will be realized by simply reducing the number of places where one subsystem has crushed, punctured, or cut key components of another subsystem.

In construction, there are few examples of all subsystems integrated into one unified system. The work of architect Ezra Ehrenkranz stands out among the attempts at total-system physical integration. The School Construction System Design (SCSD) project for California school districts is the most successful effort to date in physical integration (see Appendix C. SCSD—A Physical Integration Success Story). The intensive coordination between designer, engineer, manufacturer, contractor, and owner necessary to achieve an open, integrated system is a major obstacle for home builders producing only a few dozen or even a few hundred houses based on the same design. Ehrenkranz overcame this obstacle in SCSD by bringing together school districts needing to build. This coalition assured manufacturers that sufficient system/material quantities would be contracted to profitably pay the cost of retooling product lines.

Object-oriented CAD-based physical integration tools can be applied to the interface between adjacent subsystems such as plumbing and framing during the design phase. The same position-checking and interferencedetection tools can be applied to the relationships among components and subcomponents of a subsystem, such as the relationships among a roof framing member, a roof sheathing panel, and a fastener. Simple software-based coordination of material sizes, chemistries, fastening schedules, and component design can accelerate production rates, reduce first cost and life-cycle maintenance, and ultimately increase performance.

Anecdotal evidence suggests that the most common problems arising from a lack of physical integration are as follows:

- excessive floor-to-ceiling cavity depths due to limited planning of the path for subsystems,
- inadequate access for maintenance,
- missing backing material for finish-material installation,
- ductwork placed outside the conditioned building envelope,
- ductwork compressed after installation,
- inadequate space for drain-line slopes,
- cuts through critical structural assemblies for waste piping,
- cuts through critical structural assemblies for electrical wiring,
- engineered-wood structural elements modified in the field to accept mechanical equipment,
- missing or improper flashing installation, and
- missing water pipe insulation.

The lack of statistically sound data documenting the productivity and performance losses due to physical integration failures is a significant barrier to benchmarking current practices. It is also a barrier to evaluating the costs and merits of design and construction practices aimed at increasing the level of physical integration. Statistical sampling and analysis of designed and on-site practices leading to physical conflicts between subsystems must be completed prior to the development of tools and practices for physical integration.

Modularity in Residential Construction

Since the development of the balloon frame in the mid-1830s, the home-building industry has adopted the 16-inch framing increment as an industry standard. Manufacturers of plywood reinforced the 16-inch planning module with the 48- by 96-inch panel dimension to ensure the rapid adoption of plywood by the home-building industry. Since the 1930s, window, cabinet, insulation, and drywall manufacturers have developed products compatible with the 16-inch dimension.

Programs such as the American Plywood Association's MOD 24 (APA 1970) and Engineered 24-inch Framing (APA 1981) and techniques such as the planning principles used in optimum-value engineering (OVE) sought to reduce construction material waste by working to modular dimensions of materials and modifying traditional framing practices with engineering-based designs for the spacing and dimensions of framing elements. These programs advocated the 24-inch framing increment to better utilize the structural capability of standard wood studs and plywood products. The 1978 HUD publication *Reducing Home Building Costs with Optimum Value Engineered Design and Construction* (NAHBRC 1978) documents research conducted by the National Association of Home Builders Research Center (NAHBRC) on design and construction methods for wood construction intended to reduce material waste and framing and sheathing costs. MOD 24 documented cost reductions on the order of 6.45 percent, or $219 (1970 dollars; $967 in 1999 dollars), while Engineered 24 inch framing was documented to save 12 percent of construction costs, or $929 (1981 dollars; $1,824 in 1999 dollars) by simply changing the spacing of framing members from 16 to 24 inches. These methods continue to be employed by builders of entry-level and low-income housing to decrease time and materials costs.

These programs concentrated on framing and superstructure systems which manufacturers of windows, wall insulation, and drywall could support with little redesign of their products or manufacturing methods. Foundation, heating, cooling, plumbing, and electrical systems have not yet entered this open system. In residential construction these subsystems are fabricated by hand on the construction site. This method affords great design flexibility but does not bring these systems into the world of integration. Without a modular or integrative approach, improvised, on-site solutions for routing electrical, water, and waste lines will continue to drill, cut, and weaken structural members in critical locations.

Physical Integration in Large-Scale Construction

Due to the constructed quantities involved and longer-term ownership, larger buildings such as museums and office buildings often approach physical integration with production efficiency, maintainability, and system replacement in mind. Meshing of subsystems was a popular strategy in the early 1960s. Meshing strategies carefully wove the mechanical, structural, electrical, and plumbing subsystems together to reduce the overall floor-to-floor height of office buildings. This approach also required additional time and resource investment in the late design stages of the project. Coordination of subsystems during the preliminary, schematic, and design development stages of the design project required architects and engineers to invest more coordination time during each stage than alternative "space reserving" strategies. For cost reasons many designers slowly abandoned the meshing strategy of total system integration. Designers and project managers also noted that the tight sequencing of trades exposed projects to significant delays if one key union had a labor dispute.

A dominant strategy currently used in the design phases includes the development of "reserved space" in ceiling and floor structures for each subsystem. For example, the ceiling subsystem might have 1–1½ inches reserved from the face of the ceiling finish to the top of the channels suspending the ceiling, lighting would have the next 6 inches above the ceiling, plumbing the next 8 inches, mechanical the next 18 inches, and the structural system 28 or so inches remaining to the top of the space.

These strategies require that subsystem components be planned (designed and drawn) at an early stage of design. Knowledge of component sizes, insulation, and slope are critical to conflict prevention and field improvisation. This is not standard practice for many designers and builders due to costs (and lack of compensation) involved in the design, drawing, and coordination of subsystems in housing. Current practices often send the design out to the field with only framing diagrams and plan locations for lighting and plumbing fixtures. Beyond locating the primary vertical waste line (which often does not fit in a standard 2 x 4 wall), those making the drawing assume field personnel will find a way to route power, switch, vent, and drain lines. Often field personnel must improvise locations and routing for primary heating and cooling ducts. The lack of complete rationalization of subsystems in the design phase continues to be a significant obstacle to achieving higher levels of physical integration.

Consequence of Modular Planning Ideas in Residential Construction

Use of these material efficiency methods in the residential construction industry has been strong among the production builders who are mass-producing house designs. The larger numbers of same or similar house designs produced by these builders enable the cost-effective distribution of design refinements (across many units constructed) necessary to optimize spatial functionality, user desires, and material use.

The “fail-safe” assembly method (Hernandez 1993) practiced in conjunction with total quality management programs by many manufacturers of components for the machine tool, automotive, and aerospace industries has all but eliminated discrete quality control departments. Use of the fail-safe assembly method makes the next downstream operation impossible to complete with an improperly assembled part or subassembly, shunting the defect to a rework cycle.

It would be hard to find residential construction workers who have not had to spend more time or material on their subcontract because the crew who just installed a subsystem ahead of them did not know or care that some other trade would be installing in the same location. These “over the wall” problems (“It’s not my problem; it’s YOUR problem”) made by discrete subcontractors can be dramatically reduced with a combination of redefined labor boundaries and implementation of “fail-safe” design of subsystem connections and components. Redefined labor boundaries must focus responsibility on complete construction assemblies, rather than on single subcontracts. The architecture and engineering research firm IBACOS is experimenting with cross-trained trades organized as the grounds team, superstructure team, envelope/enclosure team, and systems/finishes team. Ideally, this approach would reduce the performance impacts on subsystems by training the assembly teams in the relationship of their particular work to the performance of the whole house.

Many design tools currently supporting the physical integration of subsystems and subsystem components for housing are limited to CAD software with minimal object-orientation intelligence. The cost-competitive environment for housing design limits or eliminates rationalization of subsystems and interference checking necessary for physical integration. At this time there is an opportunity to take advantage of the dominance of CAD software in the design and construction communities to begin the transition toward object-oriented CAD software. Object-oriented CAD enables designers to select predefined objects (manufactured products) from menus and place them in the design. The objects bring intelligence with them. With this intelligence, a window can determine the type and thickness of the wall it has been placed in, bring the necessary framing and lintels to the drawing, update specifications, and send its performance characteristics to linked engineering software. These links enable real-time feedback to the designer on the cost, productivity, and performance impacts of a design decision.

The residential design and construction industry does not have a standard format for the data each object should carry. Development of an object-oriented resource kit for residential design and construction is a necessary step towards systems integration in housing. The use of object-oriented CAD systems is not new to the heavy industry segment of the design and construction communities. For years the designers and builders of heavy industry (chemical refineries, manufacturing) have employed interference checking, ergonomic analysis, production planning, and engineering-based analytical tools. Adapted to the unique materials, tools, and practices used in housing, similar tools could provide near-term gains in physical integration.

PERFORMANCE INTEGRATION

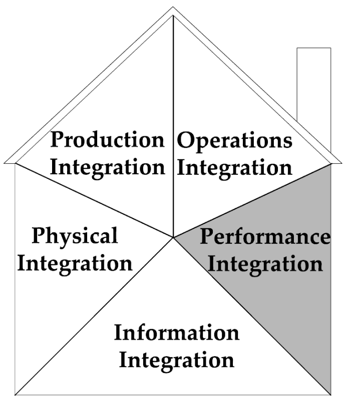

Figure 3.4: Performance integration

Performance integration—making the many parts perform as one—can be considered from within a subsystem (ductwork seals and heating, ventilating, and air conditioning [HVAC] performance) and across multiple subsystems (cooling duct, insulation, vapor barrier). Designing for performance of discrete subsystems is well matched to the current form of contracts and subcontracts (it is not difficult, for example, to hold a plumber responsible for drains not draining). But as performance expectations increase, it is necessary to coordinate the interactions of one subsystem on another. (For example, if the windows are larger on the south side and the floor mass is increased, the design can support a reduction in furnace and duct size.) Software tools such as "Energy Scheming" (Brown 1997) or "Energy 10" (National Renewable Energy Laboratory 1999) supporting this kind of "what if" method of performance increase are readily available to housing designers. But tools supporting the "what if" method generally do not consider the subsequent impact on structural members. Structural analysis tools do not consider the impact of ductwork or air conditioning on condensation or its subsequent impact on fiber saturation and so on. Each tool assumes its own discipline is at the top rung of the ladder when decision making occurs.

At the commercial scale of construction, there is a trend towards benchmarking the performance of subsystems through a process known as total building commissioning. This process involves third-party certification of performance, consumption, and maintainability, which may have a place in housing as subsystems and controls become more complex and as consumer tolerance for adjustment, rising operating costs, and frequent maintenance decreases.

Beyond the minimum levels of performance required by building regulations, there is little agreement on whole-house performance across the fragmented residential design and construction industry. Contributing factors include the following:

- minimal communication between standards groups across disciplinary lines;
- geographic variation in hazards and operating environments;
- competing values between housing producers, buyers, and government (thermal, structural and disaster performance);
- lack of agreement of singular design methodology for housing;
- absence of design tools for integrated assemblies (discrete disciplinary tools are available, but connections between structural, electrical, mechanical design are not on the market);
- lack of agreement on the criticality of spatial performance across user/owner age and physical ability grouping;
- lack of agreement on the criticality and assessment of indoor air