LOGISTICAL ASPECTS OF PREFABRICATION

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The cynic's history of prefabrication tells of obsessive idealists with an aversion to messy earth-work and to blue collars. These Edisons and Wachsmans devoted untold effort, promotional fervor, and capital to their prefabrication dreams; seldom to great profit. The enthusiast's account would describe these brilliant visionaries as stymied by timid bankers, protectionist unions, and uneducated customers. They'd point out that progress is inevitable in spite of such dullard opposition, and cite the enormous success of the mobile home, which has for half a century dominated the market for small detached houses. Both narratives oversimplify. Some building has always been carried out off-site, from timber frames pre-crafted in the woods of New England, to the catalogue houses of the twenties, to recent container fit-ups. But each species of prefabrication comes and goes. The viability of a prefabrication method seems to depend less on the inexorable march of technology than on the changeable logistical conditions in which a particular building site finds itself. It is these logistical imperatives that will be explored here. This essay presents no new historical data or technical advances. It looks at some fundamental conditions of off-site and on-site building, conditions so ordinary that they might easily be overlooked - by cynic and enthusiast alike. What it offers is some new perspectives on manufacture, construction, and transport: for example some critical ratios of cost and value that delimit the viability and scope of off-site processes. Elementary ideas such as these suggest a different future for building than were envisioned in twentieth-century predictions or invocations of the factory.

The first section of the paper draws a distinction between construction and manufacture, not as on-site and off-site work, but as volumetric expansion or condensation of value. The added difficulties of shipping expanded material are among the fundamental impediments to prefabrication. So we look at transportation in some detail. Adding shippable value to building materials is not straightforward: potential forms of value are explored in section two. Section three investigates some costs of the factory that a site builder needn't pay. This leads to the fourth section, which does take a historical view on the evolution of factory technology, but again emphasizing spatial distribution. If any pattern can be discerned in the industrialization of building, it is that technologies move from centralized factories toward the site, rather than the other way around. By way of conclusion, possible forms of a post-industrial building industry are proposed.

SPECIFIC AND SHIPPABLE VALUE

Manufacture vs. Construction

That manufacture and construction usually take place off-site and on-site doesn't tell us much about either. More to the point, manufacturing tends to concentrate value added while construction expands the volume of input materials. Sawmilling is a manufacturing process that roughly doubles the value of raw materials. Furthermore, it transforms approximately three truckloads of logs into one of lumber, so that volume-specific value increases six times. Accordingly, sawmills tend to be located close to the forest: to save trucking. House framing, on the other hand, is a construction process. Building a floor, a roof, or a stud wall expands material by a factor of about five, depending on specs and details. Combining these assemblies into a building expands them again, by another factor of four to five. These framing processes combine to reduce density by a factor something like twenty. So, while framing also roughly doubles the value of material, volume-specific value falls by a factor of ten. Such processes of volumetric expansion tend to be located farther from the sawmill and closer to the site; again, to save trucking.

The greater the reduction in specific value, the happier the site builder should be: their aim is to make a minimal material input define a maximal volume of space. Off-site builders must be careful about what they make and ship. Most factory-made building components, from simple roof trusses to windows to finished modules, represent increases in volume that constrain specific value. This is the fundamental diseconomy that all prefabricators must address, both in conceiving their products and in locating their plants. However, it may not be enough to look at value-to-volume ratios alone. There are other transportation costs besides volume.

Mass

Where the physical density of cargoes is high, mass may be the only determinant of shipping costs. A semi-trailer offers about 6,400,000 in^3 of cargo space, and is permitted to carry about 40,000 lbs. General and packaged loads tend to occupy more than 160 in^3/lb. and tie up a whole truck without reaching the weight limit. They are typically charged by volume. In fact, the general trucking industry uses a fictive "cubed" or "dimensional" weight, whereby increments of roughly 160 in^3 are assessed as weighing 1 lb. Bulk cargoes tend to occupy less than the critical volume, and are charged by actual weight.

Structural materials are dense. The net density of bundled steel varies with section, stickering, and other variables, but it may occupy only 5 or 10 in^3/lb. Concrete block occupies about 25 in^3/lb and lumber, around 60. None of these cargoes fills a truck to the maximum available height, so they are treated as tonnage. Insulation materials on the other hand, may occupy more than 1000 in^3/lb. and are sometimes shipped in specialized low-bed trailers. Fiberglass batts are compressed, first in bags and then in bundles, to approach the critical threshold of 160 in^3/lb. Much more compression doesn't pay off, as greater density would be charged by weight. The prime opportunity for prefabricators is to expand heavy materials into products near the critical density, thus making the most of the shipping volume that is available to a given weight.

Other Transport Costs

Handling also costs. If items in the order of 50 lbs. weight afford handholds, or if items in the 1500 lb. range offer forklift slots, they will cost less to ship than their unwieldy counterparts. Packages bigger than a worker can handle but smaller than a full load for a forklift or boom incur unnecessary handling cycles. Items larger or heavier or more oddly shaped than a standard industrial lift require special provisions like the trailers and booms used by truss manufacturers. The need to protect something from the weather will cost, in packaging, warehousing, or both. If an item also needs reinforcing against structural deformation or protection from shock, superimposed packages, or other shipping hazards, costs go up again. Many building products exhibit some of these forms of awkwardness, hence the abundance of packaging in construction dumpsters. whether on-site or off.

Well-designed packaging incorporates handling points and provides weatherproofing, shock absorption, rigidity, stackability, logistical instructions, and more. It should do so at low first cost and at low disposal costs. The cheapest packaging needs neither to be purchased nor disposed of at all, because it is inherent in the product. For example, the only packaging extraneous to a mobile home is the re-sellable running gear and some fraction of the mechanical capacity of the frame.

Volume-specific value or value density are rough measures of commercial viability, but given the complexities of shipping, a more useful measure would be a ratio of the product value to the total costs of transport: volume, mass, packaging, shipping, warehousing, handling, packaging disposal, and so on. This ratio can be called shippable value. The shippable value of the self-packaged mobile home turns out to be a lot higher than its specific value would suggest. The shippable value of less complete modules or components may be significantly lower.

Route Factors

The obvious variable in the cost of a particular mode of shipping is distance, but the fixed handling costs of loading and unloading must always be considered. High loading costs increase the apparent distance; low costs reduce it. This is especially true where the ton-mile cost is low. Even in such massive and low value materials as uncut flagstone, Chinese suppliers may compete with nearer sources. Not only because moving containers by sea is very cheap but because the cost of moving stone out of a quarry and into the container is low. So the apparent distance from China is short. Transshipment within a route also contributes to apparent distance. Rail transport is cheaper per ton-mile than other forms of land transport, but usually entails transshipment from and to rubber-tired vehicles for pickup and delivery. The cost of rail-truck transshipment gives rise to the long distance trucking industry.

Another route cost or route limitation is the cross sectional area of the product or the so-called loading gage of the vehicle. Railcars are slightly wider and taller than standard trucks, but railway infrastructure is less forgiving. On highways, wider and even taller loads can be accommodated with simple additional measures. Ships have enormous cross section, but handling equipment strongly favors the intermodal container. Part of the success of the container is that it falls within the loading gage of virtually every road system. Unfortunately, this leaves a lot of unused capacity in rail routes, especially the wide gage systems such as Russia's and India's. Unfortunately, the least-common-width container is smaller than the social space required by many functions in many cultures. Had roads and railways been based on a wider loading gage (such as that envisioned by Brunel) more kinds of building module could be shipped inter-modally and overseas.

A route or mode can also be characterized by bandwidth. Scheduling is vital to construction, because a multitude of trades and processes must operate at different frequencies and are subject to different disruptions. Compared to the fixed frequencies of ship and rail carriers, the multitude of vehicle types, speeds, frequencies and regularities that coexist on the highways constitute significant bandwidth that offers construction managers great flexibility and responsiveness. Construction sites that are served by a smaller transportation bandwidth are more vulnerable to disruptions, and begin to attract higher levels of pre-fabrication. Geographically remote sites are an obvious example; the upper floors in tall buildings served by low-bandwidth (and low-loading-gage) elevators are another.

In 1980, an entirely self-contained lead/zinc concentrating plant was built integrally with a barge at Trois Rivieres on the mouth of the St Lawrence River, and then towed 3500 mi. to initiate development of the Polaris mine on Little Cornwallis Island, 15º from the North Pole. Here it was beached on a prepared seabed and surrounded by an apron of fill. In a sense, there was no loading or unloading separate from construction processes, so the apparent distance was shorter than the miles logged. The loading gage of the barge was exactly the size it needed to be.

The bandwidth of available transport was close to zero, because of the short ice-free season. Prefabrication was the only response to these logistical conditions. But even here, the high specific value of the self-contained plant was a factor. The author's summer construction crewmates spent two winters at Polaris doing conventional interior work on the lower-specific-value housing. The ultra-low-specific-value concentrate storage shed was erected on site of parts similar to those that would have been used anywhere.

KINDS OF VALUE

The ways of adding value to construction material are uncountable, but some basic categories are worth considering. The simplest can be called embodied work. A standard W-pattern 4/12 roof truss embodies 16 saw cuts and 8 pairs of gang-nails – nothing more. How can a factory accelerating such a small amount of site work be viable, especially given the transportation costs incurred? The great success of the roof truss industry tells us that the product contains significant value besides a few watt-seconds of work. For one thing, it inserts geometry into the building sequence not at the tail end, but near the beginning, where it has a controlling function. But the greatest value probably lies in its engineering. The truss embodies not only the maker's guaranteed design, but also the guaranteed quality of their material and fabrication process.

Mass

In vehicles, mass tends to detract from performance, but in buildings this is seldom the case. Mass in the upper parts of a tall building, especially in seismic zones, does add to structural loads. But elsewhere, whether among structural sections, finishes, service components, or what have you, weight or thickness usually contributes to performance or longevity. So exotic composites, pierced beams, and other factory-achievable methods of lightening won't often contribute to building value. The low-energy construction materials and delivery methods that characterize building construction fall short of the airborne future envisioned by a Fuller, but realistically, the energy economics of building rarely support the types of manufacture supported.

Internal and External Connections

Whether a building component arrives on site as an asset or a liability to the overall budget depends largely on how easy it is to install. A roof truss, a boiler, a window, a mobile home all manifest a large number of critical internal connections and a small number of simpler connections to their physical context. Serviced and finished floor or wall panels tend to the opposite condition. But this issue of internal and external connectivity is a matter of systems analysis more than logistics and won't be discussed here.

Radius of Viability: The Case of Cabinets

In the author's own days as a carpenter in the seventies and eighties, it was more likely for a cabinet to be built on site than in a shop. Plywood doors were rebated on three edges to accommodate any irregularities in the site-built face frame, which in turn hid any roughness in the site-built case. But a growing taste for raised panel doors and uniform spray finishes favored shop work. The low specific value of cabinets meant that shops were quite closely spaced, and not very big. In time, the higher-shippable-value doors were made by centralized manufacturers who could exploit bigger, more specialized equipment and increased buying power.

Entire cabinets shipped flat may increase specific value, if the savings in waste removed covers the additional burden of packaging. However, the flat-packed kitchen is less attractive to professional builders than to DIY consumers. The latter supply free assembly labor, and don't mind paying for the specialized hardware that enables their work. A cabinet shop is set up for rapid assembly using the cheapest of hardware. So in a commercial context, the local prefabricator may still compete with the distant pre-cutter.

Which cabinet solution applies to a given building site depends on myriad factors, but each type of shop has a distinct radius of viability, reconciling the economies of scale with shipping costs and market density. Similar calculations would apply to every part of a building supply chain. Vinyl windows can be made fairly locally from high value hardware and extrusions shipped a great distance, and somewhat lower value glazing, usually sourced closer to hand. Manufacturers of any building product, component, or module must operate within their particular radius of viability.

SOME HIDDEN COSTS IN THE FACTORY

Wrong Distance

Scaling and locating a comprehensive building factory becomes difficult. A plant may find itself shipping lower specific value components past their limit of viability, in order to support the sales of more intensely manufactured components. Conversely, the market for higher specific value components might be limited by the smaller viable radius of the lower-specific value-modules that contain them. In this case the expensive parts of the factory won't reach a market large enough to provide the required economy of scale. On the other hand, if a plant is conceived merely as a gathering and pre-assembly station of parts manufactured elsewhere, whatever savings it offers over site assembly must be set against the additional point of inventory and transshipment that it creates.

Space

A factory does provide shelter from the elements, so less construction days are lost to weather. Of course, for processes that can be executed almost as well in poor weather as fine, the cost of creating and servicing a plant may become burdensome. And for the later phases of construction, where shelter is required, a conveniently located space often becomes available to the stick builder at a low rate – in the form of the roof-tight project.

Labour Factors

Much on-site labour is provided by independent and highly competitive subcontractors. These workers represent zero payroll burden, overhead, sick days, and HR costs. Early factory workers required less training than craftspeople wielding hand tools. Today's sub-trades each perform such a narrow range of operations that this advantage has reversed. Furthermore, because each construction pieceworker owns a small set of specialized tools, capital is seldom idle and investments are quickly amortized. In this self-regulating, self-motivated, and mobile labour force, no worker spends longer on a job than is necessary. Equipping and scheduling a fixed labour force to accomplish complex tasks through a centrally managed system will rarely be as efficient.

Building processes are more thoroughly industrialized than their outdoor location suggests. Any capitalist would approve of the efficiencies of mobile pieceworkers. And yet the socialist might enthuse that every worker owns their own portion of the means of production: a truck, a mobile device, and a small bag of tools. Both parties would point to the scant need for a managerial class.

Indeed, it is the inability of this decentralized system to respond to managerial inputs that makes design in this sector so hard to achieve. Maybe the architect's enthusiasm for the factory is not due to the dubious economics but to the promise of exacting design control.

DISTRIBUTION OF TECHNOLOGY

Early mill towns were clustered around rapids and waterfalls. Coal-fired steam encouraged factories to disperse, but they were still powered through massive hierarchies of line-shafts and belts. Machines had to be designed and positioned accordingly. The transition from steam to electricity in the interwar years further freed up the location of the factory; it also freed up its internal organization. The first AC motors worked through shaft and belt systems, but as motors became smaller and more dispersed, these systems disappeared. Machinery could be driven by onboard motors sized and positioned as function demanded. The shop floor could be rationalized, so production efficiencies were gained even where electricity was expensive.

By this point, light frame construction was well established. Framing lumber, boards, and moldings were no longer crafted on site, but produced in distant mills. Site carpentry was largely reduced to sawing prepared pieces to length and angle and nailing them together. The cutoff function requires sheer energy and precision rather than craft judgement and is better accomplished by machines than by hand. So these interwar decades saw the flowering of the precut catalogue house. Whatever packaging was required by some of the more delicate elements was offset by mechanization of saws and planes. Pre-cut wood buildings were not only a North American phenomenon. In Niesky, Germany, the firm of Christoph and Unmack precut many types and sizes of building, both for the domestic market and the colonies. This firm worked with log building and traditional German methods, but also imported American ideas of light construction. It was at this firm that a young architect by the name of Konrad Wachsman spent formative years.

AC electric motors continued to shrink in size and to proliferate with rural electrification. In 1924 Edmond Michel and Joseph Sullivan founded what was to become the Skil corporation, to develop and produce Michel's invention of the hand-held circular saw. From this point, as portable tools became more effective and affordable, the precut house began to loose its competitive edge. Portable cut-off tools saved much the same labour as their factory equivalent, but eliminated the shipping of vulnerable components. They also accommodated locally generated or influenced design.

The nineteen-seventies witnessed a short-lived form of prefabrication, the factory-made sheathed stud-wall. The units were typically too unwieldy to be manhandled and too small to justify a crane. Nonetheless, they survived for a time. They may have reflected the labor savings of the pneumatic nailer. Initially this was a rare and expensive instrument, and compressors were bulky. As pneumatics became cheaper and portable, many nailing plants shut down.

Although small AC motors allowed factories to organize themselves around the product, one force for centralization remained. Factory assembly of parts depends on exact control of form and dimension, and until the latertwentieth century, this was achieved by patterns, jigs, and fixtures. These devices were massive and fragile, so not amenable to shipping, and in many cases matched to each other. Factories thus organized themselves around central tool and die depositories. With the advent of CNC, control information was no longer stored in material form but as numerical code. Code is easy to transport and in some manufacturing sectors this has permitted enormous decentralization of supply networks.

Architectural CNC is beginning an important transformation. Continuous-duty CNC routers still cost in the tens of thousands of dollars, and must command a significant territory in order to earn their keep. They are versatile in what they can make, but perform basic cutting operations expensively. Router bit edges cost about ten times as much as a saw tooth, and as there are only two or three of them on a bit, they must be replaced more often. Yet most operations required to make building parts are not that complex, and within each trade they are limited and specialized. In the era of AC proliferation, a wide array of cheap power tools has met that varied demand. We can expect CNC technology to play a greater role on site over the next decades, as cheaper, more specialized and more portable CNC tools come to replace the universal machine. Some will be highly portable in the manner of a compound mitre saw, others truck-based, in the manner of a seamless gutter service.

PROGNOSTICATION

Builders have been doing off-site work for millennia: wherever it saved transportation costs and simplified construction. Different types and levels of precutting and pre-assembly have flourished in different times and places. The early evolution of industrial technologies favored economies of scale and led to increased centralization; as technologies evolved, they proliferated and dispersed. Information technologies such as digital manufacturing tools and cloud-based mobile devices are furthering this process of post-industrialization. Our hybrid, responsive, heterocentric, and deeply distributed construction industry was a leader of this process, not a laggard. The centralized factory was never a major player in building and is now an anachronism. The conventional distributed system of construction will continue to create innovative fabrication and pre-assembly solutions, but in response to specific commercial and logistical contexts.

This low-management building system of competitive and interchangeable pieceworkers is very lean, but it has difficulty accommodating the informational demands of architecture. In this self-managed system, what look like minor demands for formal simplicity and geometrical coordination end up costing astonishing premiums. So the level of design in our residential, commercial, and industrial landscape is rather low. For architects, the real attraction of prefabrication was probably not its dubious economics, but the design control that it promised.

Computer controlled equipment will move to the site as power tools did in the mid twentieth century, and as pneumatics did in its later decades. The building factory will then be complete: it will be everywhere. There will be a need for coherent design information to run the distributed factory. The need will not be provided by cumbersome and amorphous building information systems. It will be filled by formal languages open enough to stimulate competition and creativity yet closed enough to provide efficient coordination of form and process. It could be the architects' dream of the factory come true. If architects build it.