ASSESSING ALTERNATIVE PREFABRICATION METHODS: LOGISTICAL INFLUENCES

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Abstract

Any construction project that is completed on-time at the lowest total cost requires the consideration of logistics processes and economics. This study investigates the cost implications of moving and transforming materials in various materials network configurations associated with popular prefabrication construction methods. Efforts focus on the trade-offs that exist among contract-to-completion times, transportation costs, and assembly costs for the alternative construction methods. The findings suggest that the competitive advantage of prefabrication methods can be enhanced through an optimal combination of reduced construction times as well as the number, distance, and configurations of materials and sub-assembly shipments.

Introduction

The expression “time is money” appropriately applies to commercial initiatives, particularly construction projects. The duration of a construction project – from the time the contract is initiated to when the structure is completed –has a direct impact on the cost of the job. Bids from competing contractors, costs of construction loans, and earnings streams of business enterprises dependent on the finished structures are all affected by the time necessary to construct a building.

Prefabrication is a construction alternative that is primarily chosen because of its ability to reduce the total time for completing a project. Prefabricated construction refers to the utilization of sub-assembled structural components generally manufactured off-site (CII, 2002). From fully-manufactured buildings to those assembled from modularized, panelized, or even pre-cut components, the incremental degrees to which prefabrication can be employed is limitless. The reduction in construction times that these approaches provide can be mainly attributed to the degree of independence between site preparation and sub-assembly, more dependable job scheduling, and greater production efficiencies at the prefabrication sites as well as at the construction site (CII, 2002; Haas and Fagerlund, 2002; Kupitz and Goodjohn, 1991; Tatum et al., 1987).

While the reduction in construction time is perhaps the most visible and important benefit of prefabrication techniques, the costs associated with off-site activities pertaining to the movement of materials can impact the extent to which a particular level of prefabrication is economically feasible. The number, distance, and configurations of supply and sub-assembly shipments can add tens of thousands of dollars to projects of even a modest size. To gain further clarity regarding this issue, the effects of logistical activities associated with common prefabrication processes were investigated. The time and cost relationships that exist among these variables were identified, modeled, and analyzed. Efforts focused on the trade-offs that exist among contract-to-completion times, transportation costs, and assembly costs for alternative construction methods across multiple applications. Recommendations for strategies and configurations for improved economics are then offered.

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Logistics Processes and Variables

In the world of buying and selling consumer goods, logistics management involves the coordination of a variety of interrelated activities aimed at achieving optimal service and cost performance (Ballou, 2004; Stock and Lambert, 2001). Each activity can be classified as falling into one of three high-level functional areas: customer service, inventory control, and transportation management

Customer service activities involve identifying and locking in order fulfillment targets, ideally at the customer and stock-keeping unit level. These market-oriented metrics subsequently influence the service and cost objectives of the remaining two functional areas. Upon the identification of order fulfillment requirements, the levels of both inventory and transportation capabilities are collectively determined to support order fulfillment targets at the lowest total operational cost. While construction projects exhibit logistics variables similar to those found in conventional manufacturing processes, variations exist in how they are measured and applied.

For built to order (BTO) projects, the structural specifications, price, and completion time as stipulated in the contract is directly comparable to an order fulfillment target of a consumer goods supplier. This deliverable then would guide subsequent decisions regarding the amount and frequency of purchased inventory and the transportation activities required to support them. Within a construction environment, however, materials inventory are not recognized and measured in the same manner as consumer goods inventory. A commercial building is fixed asset and no alternative exists but to purchase a predetermined volume of materials as dictated by the building's specifications and the sequence of construction activities. Materials that are purchased earlier in the project will generate higher carrying costs than those purchased at later stages but the overall carrying cost effect would appear to be negligible.

The highest cost among the major logistics functions is most often attributed to transportation operations (Stock and Lambert, 2001). For most supply chain applications, the total cost from buying transportation services reflects the modes that are selected (i.e. air, ground, and water) as well as the distance and direction of shipments moving via those modes. Consistent with the adage "you get what you pay for", the per-pound freight charge for a small shipment that is rapidly transported over long distances is typically higher than that for a larger shipment that is transported at a slower speed over a shorter distance. Exceptions to this rule of thumb can be traced to the supply and demand of transportation equipment, non-linear ton-mile economics, and any additional services provided by the carrier.

Construction methods utilizing off-site prefabrication will naturally bear higher costs for transportation than conventional on-site methods. This can be attributed to any combination of the following: an increase in the total number of shipments, the distance and direction of shipments, and shipment configurations requiring higher-cost transportation capabilities.

In addition to transportation services, the facilities and manpower necessary for constructing a building will be reflected by the construction methods used. The nature of assembly processes and their locations in relation to those of their suppliers and to the building site will be important factors in determining the impact of logistics variables. Conventional, on-site "stick" construction will typically require less fixed overhead and less transportation activity than methods employing panelized or modularized components that are assembled off-site.

This paper focuses on the direct costs associated with the transportation alternatives pertaining to supply and assembly configurations of the various alternatives. Because of effects purported to be negligible in a close BTO operation, inventory carrying costs were not included in this analysis. Likewise, off-site overhead of the fabricators is considered a sunk cost and has not been incorporated into the model.

Method of Analysis

The core construction alternatives analyzed are off-site module prefabrication, off-site panel prefabrication, and traditional site-built construction. Each exhibit behaviors that can impact transportation needs and costs in various ways.

Guided by existing literature, a simple flow diagram was initially mapped to assist in the identification of common processes, locations, and logistical relationships required by alternative construction methods for the same project using the same suppliers. Figure 1 identifies the value-add tiers relevant to this investigation and the supply lanes that link them. It displays an aggregate supply lanes for shipments moving from origins A directly to construction site B as well as for shipments from the same origins to site construction site B via fabricator sites C.

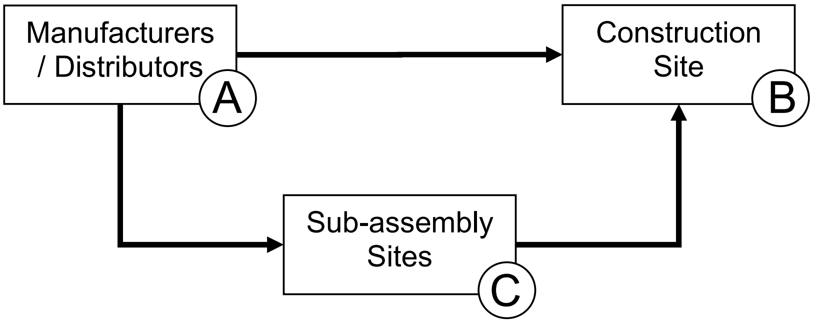

Figure 1: High level material flows for on-site and prefabricated construction alternatives

Traditional on-site construction efforts are supplied through lane A-B. Meanwhile, off-site sub-assembly efforts require that materials first move via lane A-C for sub-assembly and then move to the construction site via lane C-B. If supply lanes A-B and A-C are understood to be fairly similar based on the same bill of materials, shipment size, distance, and direction, then the combined time and costs effects of prefabrication activities at site C and the movement of materials via lane C-B is expected to be where significant effects exist in determining the most cost-effective method of construction.

Based on this framework for experimentation, relationships among the fixed and variable costs reflective of the resources and processes of actual construction operations were used to help build a more-detailed model. Comparative logistics scenarios for each alternative construction method were then created to better identify shared and isolated effects. The construction methods analyzed were:

a) No off-site prefabrication (traditional)
b) Panelized segments constructed off-site
c) Modular segments constructed offsite
d) Hybrids consisting of two or more of the above alternatives

Various levels and configurations of modularity require various transportation capabilities. Transportation alternatives for this study were limited to highway modes (e.g. 40’ flatbed, 53’ dry van) including oversized, permitted loads. The per-mile transportation rates based on shipment types that support the construction of a 3000 square foot structure are provided in Table 1.

Table 1: Shipment count and characteristics, by construction method, to supply materials for a 3000 square foot structure

Shipment Type	Average Shipment Weight	Number of Shipments	Rate Per Mile	Minimum Charge
No Pre-Fabrication, 53’ Dry Van	37,500	4	$2.00	$300
Prefab Panels (20%-70% density loss), 53” Dry Van or Flatbed	20,000 - 30,000	5 - 7	$2.00	$300
Modules, Standard Load, Flatbed	16,000	10	$2.00	$300
Modules, Wide Load (8.5-12 ft.)	24,000	7	$7.00	$900
Modules, Wide Load (>12 ft.)	30,000	5	$15.00	$2,000

Per-mile transportation rates and minimum shipment charges were sampled from archival and web-based commercial sites on a basis. They were plotted and then averaged using line of best fit. Wide variations existed among the rates, particularly for local deliveries and oversized shipments. This could be attributed to the lack of uniformity in overhead allocation and equipment utilization among these specialized carriers. Additional validation was provided by two transportation professionals who reviewed the means and spread of the values.

For each scenario, the specifications of the finished structure as well as its site were held constant as time and total cost effects due to shipment volumes, configurations, and distances as well as opportunity costs of non-operating commercial enterprise were assessed.

Across multiple construction projects, huge variations in building specifications and transportation rates can exist. For example, modular construction can be used to construct small retail shops as well as multi-storied commercial structures such as the twenty-one floors of the Hilton Palacio del Rio hotel in San Antonio, Texas. Also, as earlier explained, oversized highway shipments can present large per-mile rate variations depending on shipment size, permits, among other factors. Therefore, key assumptions were required to help define and limit the scope. For each scenario,

a) Finished commercial structures are built under contract to the same specifications

b) Structures can be built using any construction method (i.e. modules, panels, kits, and traditional site-built) or any combination of methods.

c) All finished structures will bear a structural weight per square foot of 50 pounds and a construction cost to the customer of $100 per square foot. (averaged data from a variety of sources; e.g. Building Construction Cost Data, 2005)

Scenarios are differentiated by applying building sizes ranging from 3000 to 12000 square feet. Supply origins will first be held constant and then localized. Inventory carrying costs, construction loan interest, and off-site overhead were not included as variables.

Results

Interpretations of the data derived from the analysis are consistent with what is observed in a variety of supply chain environments. For example, manufactured products like potato chips that entail less density thus higher per-mile transportation costs than does its raw materials (i.e. potatoes) will put pressure on the manufacturing site to locate nearer the market. The data provided in Table 2 support this notion. Total costs for transportation services that support the supply of materials for finished structures of 3000 square-feet and 12,000 square-feet in size are provided. Each shipment type represents a sole application of that type to the project. That is, data for applications of mixed shipment types to the project are not listed.

The lanes identified by Figure 1 are also indicated. The two sizes define the range of sizes studied are used for the sake of efficiency in conveying the cost differences among shipment type (based on size and configuration), the miles traveled, and the total volume of materials moved. Transportation costs applying to finished structures of other sizes supplied over varying distances can be readily calculated by shipment type using this table because there are no multiplicative or exponential relationships among the variables as modeled. Calculations for projects of mixed technologies and/or shipment types could be approximated by weighed averages based of the percentage of usage or application among the variables.

Table 2: Total Transportation Charges per Lane for the Alternative Construction Methods (for 3,000 square-foot and 12,000 square-foot structures)

Shipment Type	3000 Square Feet				12000 Square Feet			
	25 miles	trans$ per sf	200 miles	trans$ per sf	25 miles	trans$ per sf	200 miles	trans$ per sf
A-B: No Pre-Fabrication	$1,200	$0.40	$1,600	$0.53	$4,800	$0.40	$6,400	$0.53
A-C: No Pre-Fabrication	$1,200	$0.40	$1,600	$0.53	$4,800	$0.40	$6,400	$0.53
C-B:								
No Pre-Fabrication	$1,200	$0.40	$1,600	$0.53	$4,800	$0.40	$6,400	$0.53
Prefab Panels (70% density loss)	$2,100	$0.70	$2,800	$0.93	$8,400	$0.70	$11,200	$0.93
Modules, Standard Load	$3,000	$1.00	$4,000	$1.33	$12,000	$1.00	$16,000	$1.33
Modules, Wide Load (8.5-12 ft.)	$6,300	$2.10	$9,800	$3.27	$25,200	$2.10	$39,200	$3.27
Modules, Wide Load (>12 ft.)	$10,000	$3.33	$15,000	$5.00	$40,000	$3.33	$60,000	$5.00

Table 2 also provides the transportation cost allocated per square-foot for the finished structure. This is helpful for determining how the type or mode of transportation used can impact the overall cost of the building. Based on the findings, the greatest deterrent to the geographic market expansion or proposing competitive bids as they apply to prefabrication technologies is the distance from the fabrication shop to the construction site and the type of transportation service used. Total cost differentials for the primary shipment types and distances traveled for a particular scenario are illustrated by Figure 2. At face value, large oversize loads seem to exhibit the highest total costs even with fewer total loads.

It is important to note that the values as they exist in Table 2 and Figure 2 should not be interpreted as either good or bad. Because trade-offs exist among the various operating assets and processes, the total cost of a particular construction method may be the lowest among competing alternatives even though the transportation cost by itself was the highest in the group. The cost for moving five oversized loads that were needed to assemble a 3000 square-foot building, for example, may have allowed for a particular prefabrication process that created a greater savings in construction costs and project time.

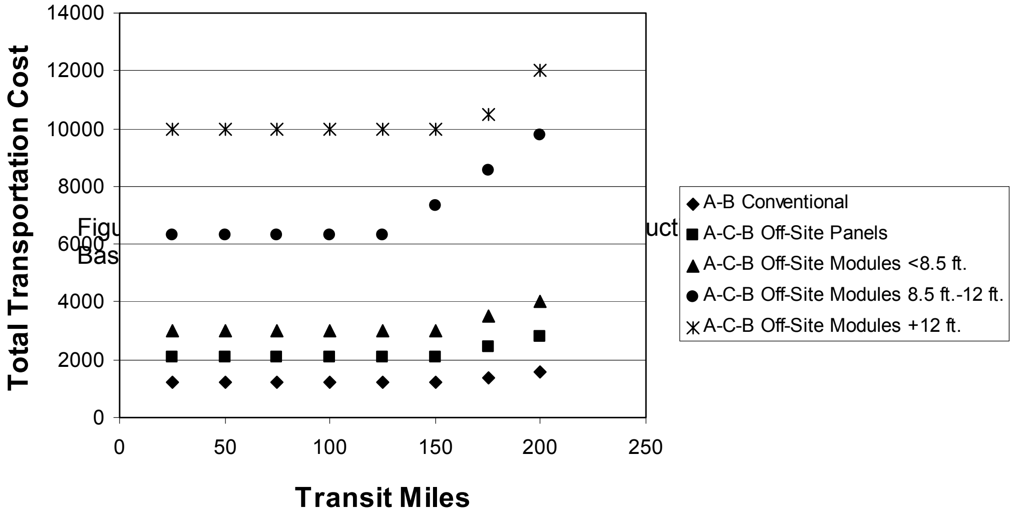

Figure 2: Total Transportation Charges per Mile for Alternative Construction Methods (for a 3,000 square-foot structure)

The rates, configurations, and distances for shipments in and out of a fabricator's facility can provide insight into sourcing, site location, and module design. In referencing Figure 1, total transportation costs from suppliers to the construction site have been calculated for the various construction methods based on the sole use of the shipment type noted. They pertain to a project involving a 3000 square-foot structure and supply legs of 25 miles and identified as:

a) A-B, Conventional On-site Construction: <u>$1200</u>

b) A-C-B, Panels with 70% density loss at site C ($1200 for four inbound loads moving 0 to 150 miles + $2100 for seven outbound loads moving 0 to 150 miles): <u>$3300</u>

c) A-C-B, Modules, no permits ($1200 for four inbound loads moving 0 to 150 miles + $3000 for ten outbound loads moving 0 to 150 miles): <u>$4200</u>

d) A-C-B, Modules, with permits ($1200 for four inbound loads moving 0 to 150 miles + $6300 for seven outbound loads moving 0 to 125 miles): <u>$7500</u>

e) A-C-B, Modules, with permits ($1200 for four inbound loads moving 0 to 150 miles + $10000 for five outbound loads moving 0 to 125 miles): <u>$11200</u>

Discussion

Modularity not only applies to the construction of a building. In manufacturing circles, using and integrating of common form factors or semi-finished components across multiple differentiated outputs has been highly successful for growing revenues and minimizing procurement and transformation costs (Zinn and Bowersox, 1988). Multiple automobile models assembled at the same plant, for example, may be built with common parts and sub-assemblies such as engines, chassis, and body panels. In any event, integrating standardized sub-assemblies into a process is intended to strike the balance among acceptable levels of customization, reduced delivery times, and cost containment (Waller et al., 2000). Similar effects are also expected when prefabrication construction techniques are applied. The results are truncated project times, greater production efficiencies, and acceptable levels of quality for a variety of finished structure that are accepted by the market.

Various logistics factors have been investigated regarding their impact on the feasibility of various prefabrication construction strategies. It was determined that building specifications, the relative value of the materials, as well as logical and tested procedures used for assembly did not allow enough opportunity to significantly reduce in-process inventory levels. Transportation cost factors, however, did play a critical role in determining the economic feasibility of prefabrication. The importance of transportation activities as they relate to the total cost of a supply chain have traditionally been marginalized in favor of asset utilization strategies such as flexible manufacturing, inventory minimization, and outsourcing. This is perplexing because total transportation expenses represent the highest cost of any supply chain network.

Construction time is also expected to decrease as the degree of off-site modularity is increased. This phenomenon will drive savings in construction loan interest and forgone operational earnings but based on the evidence derived by the research, other operating costs, particularly those emanating from transportation activities can off-set other savings. The level of transportation service required of a particular shipment will also help in determining the cost. For example, expedited delivery or oversized, permitted loads will require added resources and therefore, increase the rates. Based on the findings, oversized, permitted shipments may be the greatest operational threat to the growth in off-site modular construction. Increased distances for these shipments further exacerbate this effect.

Conclusion

Based on the results of this study, it is recommended that designers of modular construction methods incorporate lean manufacturing principles as they create solutions that are flexible enough to provide product variety, fast enough to offer marked reductions in construction times, and minimize total delivered costs to better compete with other construction alternatives.

A hybrid process that incorporates optimum assembly and logistics processes is envisioned. A combination module and panel solution, for example may add only a week to the project's duration but at a level of operational cost saving to make it worthwhile. Standardization of core materials for sub-assembled component and base modules that conform to conventional transportation equipment and services may be also included. Finally, if modular construction is less expensive when sub-assembly occurs closer to the market, then mobile prefabrication shops that source materials locally may offer the ultimate solution.

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