The Impact of Subcontracting Practice on Building Construction Automation: A Case Study on Building Prefabrication

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ABSTRACT

Pressured by labor shortage, quality requirements and tight construction schedules, building constructors are seeking automated technologies to resolve these unfriendly conditions while achieving the targeted profit. For the past decades, numerous automated concepts are being incorporated into conventional construction methods to form a composite construction technology for producing more favorable results. When a new construction method is introduced, the organization of the construction team, particularly related to the subcontracting practice, is also subject to changes. The impact of such changes on the adoption of the new technology needs to be carefully examined to ensure the overall success. This paper first reviews the subcontracting practices in the construction industry. Then, the impact on subcontracting practices when automated construction is considered is analyzed through the subcontracting cost structures of the general contractor and the subcontractor. Based on preliminary case studies, the result of this research indicates that in order to achieve maximum benefits through automation, vertically integrating or internalizing some of the subcontracting professions to the general contractor's organization is necessary.

1. INTRODUCTION

Due to the scarcity of land in metropolitan areas, the construction of high-rise building is seen as a major solution for space demand on housing and office/commercial use. For building investment, the time and the cost required for construction are two predominant factors affecting the demand-supply market mechanism. For the private investment in particular, the competitive edge resides in the investor's ability to deliver the end product on time and with superior quality, preferably enough to compensate the price premium per space unit by quality differentiation. These owner requirements, accompanied with labor shortage and strict regulations on worker's safety and environmental protection, force building constructors to adopt automation concepts and technologies to ensure their survival and success.

Conventionally, the building constructor does not involve itself into the physical construction work but takes the role of a general contractor to supervise the performance of its subcontractors. The two primary reasons for it to do so are (1) to achieve the economies of scale for managing the construction firm in dynamic business conditions, i.e., recessions and booms, and (2) to spread construction risks to other parties. For most building construction projects, the number of work items can easily grow up to the range of hundreds. Individually, each work item consists of only a tiny portion of the entire project. Therefore, it is uneconomical for a general contractor to be specialized, by maintaining a sizable work force and/or the associated equipment, in one or several trades or specialties. As the firm's workforce is kept minimal or totally removed, the firm's management and related capital expenditures can also be greatly reduced. On the other hand, subcontracting is an excellent means for a general contractor to exercise cost control while sharing part of its risks to other parties. Before subcontracting, the general contractor will perform a very detailed quantity survey. Referred to, but not limited to, the quantity from the detailed survey, the subcontract is usually unit-priced and includes such clauses which will transfer the general contractor's risks in the main contract to the subcontractors.

When an automated construction method is introduced to the construction process, this balanced subcontracting framework is under re-configuration as the division of construction work, pricing of the subcontract and the mechanism of risk sharing may all be altered. Since the general contractor is not involved in the physical construction work, it has to rely on its subcontractors to adapt to the automated method and to produce fruitful results. In practice, this may not be any easy task. This paper concentrates on the impact and, perhaps, the difficulties which will arise from this aspect. For the convenience of discussion, related issues and case studies will focus on the structural portion of building construction. The example of automated construction methods examined in the case studies is related to building prefabrication, which has become a prevailing technology for high-rise building construction in the Taiwan area.

2. THE SUBCONTRACTING PRACTICE IN CONSTRUCTION

If the structural portion of building construction is considered, including the construction and finishing of slabs, columns, girders, beams, exterior walls, balconies and stairs, the types of work items which will be subcontracted are shown in Table 1. For all ten work items, the nature of the subcontractors' end product is subject to differing construction specifications. Labor-intensive, on-site production is still the predominant means of executing construction tasks. The comparison in Table 1 indicates that by using labor-intensive, on-site production methods, subcontractors can freely move from project to project and expand their work volume without technological and managerial difficulties. Under this circumstance, subcontractors are able to maintain lean production and contain risks to reduce costs.

Closely examined, the subcontractors to perform the work items in Table 1 can be distinguished into three groups, which are (1) labor only subcontractors, (2) supply/labor subcontractors, and (3) material suppliers. Subcontracting related to rebar work, concrete placement, wielding, equipment operation, masonry, tile placement, and plastering belongs to the first group; formwork, scaffolding, and painting are related to the second group; and the procurement of plywood, rebar, pre-mixed concrete, wielding supplies, bricks, tiles, and other material items and tools are related to the third group. Price negotiation plays an important role in all three types of subcontracts. Time and quality considerations of the general contractor are, for the most part, unexpressedly conveyed to subcontractors and material suppliers through years of field practice and informal personal relationships. The contractual relationship between the general contractor and the subcontractor is normally limited to the scope of work within the construction project. Alternatively speaking, point transactions are predominant; although there may exist the possibility of recurring working relationship for all three groups and some form of long-term procurement contracting for the third group.

Table 1 Characteristics of Structural Work to be Subcontracted in the Traditional Method

Work Item	Characteristics of Production	Quantity of Usage	Nature of End Product
Formwork	Off-the shelf material, to be fabricated on site	Large volume	Open (for similar designs)
Scaffolding	Off-the-shelf material, to be fabricated on site	Large to medium volume	Open (off-the-shelf mat'l)
Rebar Work	Standard rebars, to be prepared and assembled on site	Large volume	Open
Concrete Placement	Ready-made concrete to be poured, consolidated and leveled on site	Large volume	Open
Wielding	Partially done in steel plant; wielding on-site for the most part	Large volume for SRC or SS	Open (according to spec.)
Equip. Operat.	Site operation	Large volume for SRC or SS	Open (to one site layout)
Masonry	Plaster preparation and bricklaying on site	Medium to low volume	Open (for similar designs)
Tile Placement*	Plaster preparation and laying tiles on site	Large volume (non-curtainwall)	Open
Plastering*	Site operation	Large volume	Open
Painting*	Site operation	Depending on owner's need	Open

* These work items are more related to the finishing of the structural portion but must be discussed concurrently.

3. SUBCONTRACTING IN AUTOMATED BUILDING CONSTRUCTION

When automated construction technologies are to be considered, several contractual settings for the subcontract may be subject to change. The range of impact of automated construction technologies can be inferred from Figure 1. In this paper, two theoretical extremes will be highlighted for discussion, including the case where only one subcontractor is affected by the employment of the automated technology and the case where the division of construction work is redefined by plant prefabrication. If the automation technology in consideration is only related to a single work item, i.e., the jurisdiction of a unique type of subcontractor, the question incurred is related to the allocation of the ownership costs and the savings generated from applying this technology. This situation is anticipated when on-site automation such as new tools, enhanced equipment or robots is considered. It is also to be assumed that the impact of the technological change will be strictly on that particular trade of subcontractor and all other trades which work in cooperation or in sequence are indifferent to this change.

I. The Employment of Automated Equipment for a Single Subcontractor

If, for example, a single-purpose automatic equipment is to be used on site for a given construction work item, this will undoubtedly impact the subcontractors of this specialty. First of all, the reduction of labor requirement and the emphasis on using equipment for construction will change the cost structure of a subcontractor. Assuming this piece of equipment is owned by the general contractor or its affiliation, the pricing of the equipment usage relies both on the equipment's ownership cost, OC, and the level of benefits, B, which it can generate. However, if the equipment is to be used by the subcontractor, the overall benefits, B, must be fully determined by the subcontractor, whereas the owner, i.e., the general contractor, can only have partial knowledge of it.

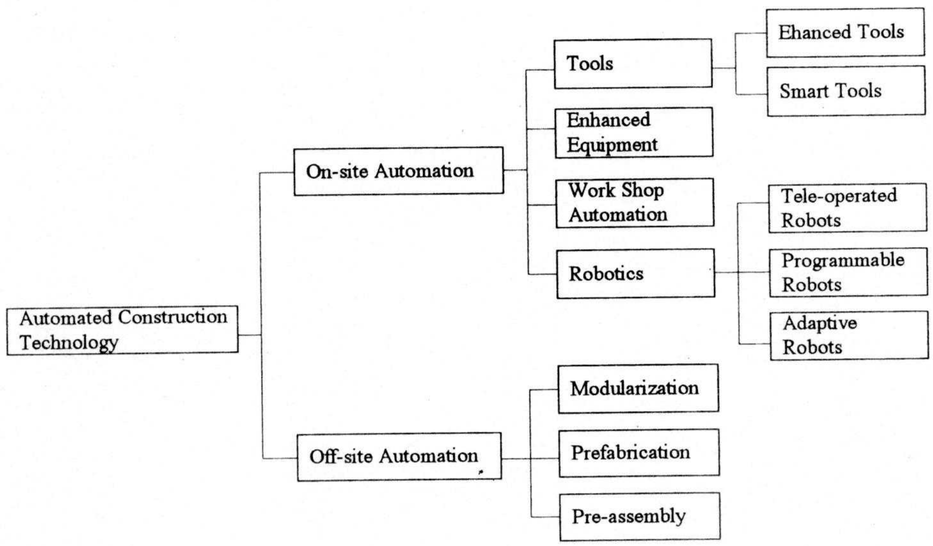

Figure 1 Classification of Automated Construction Technology

For the sake of discussion, two more dimensions can be brought in for scrutinizing, which are the quality of work and the ex post action on the equipment. Since the general contractor can only have partial knowledge of the subcontractor's action to complete the work, the general contractor's benefits which can be generated by the automated equipment are also partially determined by the quality of work. Also, the treatment of the equipment after work completion will affect the subcontractor's attitudes towards a "reasonable" pricing agreement for the current subcontract. The above relationships can be expressed in the following terms in Table 2.

Table 2 The Cost Structures of Subcontracting When Automatic Equipment Is Used

Pricing Elements	General Contractor's Cost Structure	Subcontractor's Cost Structure
1. Benefits	$I(\lambda B(x))$	$(1-\lambda) B(x) + (1-I) \lambda B(x)$
2. Costs	Ownership Cost, OC	Entry Cost, E
3. Contract Fee	$-\mu x$	μx
Total Return	$I(\lambda B(x)) - OC - \mu x$	$(1-\lambda) B(x) + (1-I) \lambda B(x) - E + \mu x$

In Table 2, λ represents the portion of the overall benefits which can actually be accrued to the general contractor, whereas a portion of $(1-\lambda)$ is "creamed off" by the subcontractor, since they can only be completely known by the subcontractor. The variable I represents the proportion of λ B(x) to be kept to the general contractor and the rest $(1-I) \lambda B(x)$ is seen as an additional reward to the subcontractor. The entry cost, E, is included as a threshold for subcontractors who are interested in contract the work. The contract price, x, refers to the costs of equipment operation and the associated material and labor, and μx indicates the fee to execute the contractor, including overhead, tax, insurance, etc. It should be noted that the quality of work is influenced by the amount of x.

Theoretically, there exists an x_{max} which will compel the subcontractor to perform the "best" workmanship and an x_{min} which results in the poorest acceptable quality. Therefore, x is treated as an index of work quality in the formulation.

With all these factors, the subcontract can become extremely complicated and will inevitably rely on a great deal of "safeguards", such as contract bonds, prepayments, insurance or even warranties, to ensure the smooth progress of the work. For the general contractor, in order to maximize its total return, there exists the opportunity of achieving x*, where $(I\ \lambda B'(x^*) - \mu) = 0$, while maintaining the total return to be greater than when traditional construction method is employed.

II. The Re-division of Work by Prefabrication

When the technology related to off-site automation is chosen, the re-division of construction work items is inevitable. Usually, the structural portion of construction consists of (1) the prefabrication of steel components and PC components, (2) the transportation of prefabricated components, (3) the erection and assembly of prefabricated components, and (4) the finishing of components connection. According to this division of work, the general contractor's reliance on conventional subcontractors is clearly reduced. The new division of work also witnesses the anew definition of the primary elements of subcontracting. Unlike the traditional method, the consideration for subcontracting is largely bound by the availability of technology and the assurance of quality rather than motivated by the ease of cost control and risk sharing.

Component Manufacturing

The manufacturing of prefabricated components are divided into eight categories of components, as shown in Table 3. Each category of components may be designed in different sizes and shapes to meet various requirements in the ensuing processes. By examining Table 2, several notions can be emphasized here. First, most structural components are to be manufactured in a plant environment rather than off-site. This is to ensure an excellent curing conditions and to achieve high precision when placing the embedment before concrete placement. Secondly, all prefabricated components can only be manufactured in small batches due to the fact that components in one category may need to be manufactured with varying settings to adjust for functional, transportation, esthetic or other considerations. Also, the end product from prefabrication is useful only to a unique design. This implies that the general contractor is essentially restrained to one subcontractor once the manufacturing process begins. The replacement of a new subcontractor for any reason will result in enormous delay and cost overrun. In addition, the subcontractor will normally require some prepayment and a pre-determined price schedule with respect to different quantities before the manufacturing process commences. Another main element in the subcontract is related to assuring the quality of prefabrication components. Generally, the subcontractor is asked to send randomly chosen samples for testing.

Component Transportation

Component transportation is commonly the responsibility of the prefabrication subcontractor. However, it can also be subcontracted out to transportation professions. Nevertheless, whether the subcontractor will transport the components by its own fleet or subcontract out this task, it is presumed that full transportation risks are transferred from the general contractor to the prefabrication subcontractor. Consequently, this task is also included as part of the prefabrication subcontract.

Table 3 Characteristics of Structural Components by Prefabrication

Component	Characteristics of Production	Quantity of Usage	Nature of End Product
Slab	To be prefabricated off-site or in plant	Low, small batches subject to various partition requirements	Limited use (only to be used for a unique design)
Beam	To be prefabricated in plant	Low to medium, depending on variations on beam design	Limited use (only to be used for a unique design)
Column	To be prefabricated off-site or in plant	Low, subject to variations on loading and embedded items	Limited use (only to be used for a unique design)
Girder	To be prefabricated off-site or in plant	Low to medium, depending on variation on girder design	Limited use (only to be used for a unique design)
Exterior Wall	To be prefabricated in plant	Medium to high, easy to be standardized	Limited use (only to be used for a unique design)
Interior Wall	To be prefabricated in plant	Low, subject to variations on surface finishing needs and embedded items	Limited use (only to be used for a unique design)
Balcony	To be prefabricated in plant	Low, small batches in different shapes and sizes	Limited use (only to be used for a unique design)
Stair	To be prefabricated off-site or in plant	Low, small batches but easy to be standardized	Limited use (only to be used for a unique design)

Table 4 Characteristics of the Final Finishing for Prefabricated Components

Work Item	Characteristics of Production	Quantity of Usage	Nature of End Product
Formwork	Specifically prepared form for pre-determined concrete pours on-site	Low volume, only applicable to connection of components	Open (for similar designs)
Rebar Work	To be prepared and assembled on site, for connecting rebars of components	Low volume, only applicable to connection of components	Open (manual preparation, indifferent of varied design)
Concrete Placement	Concrete, mixed on site to be poured, in gaps of component connections	Low volume (materials other than concrete, such as epoxy may also be used)	Open
Tile Placement	Laying tiles on sporadic surfaces, consisting mostly some labor-consuming tile cutting and arrangement	Low volume (presumably most tile placement is done in the prefabrication plant)	Open
Plastering	To improve unqualified surface finishing , as asked by supervisors	Low volume, only applicable to surfaces whose finishing is considered poor	Open

Site Erection and Assembly

The erection and assembly of prefabricated components are often performed by a specialty subcontractor other than the one responsible for prefabrication. Tight coordination between the general contractor and the erection team is utmost. The erection subcontractor's work content includes providing the workforce for wielding, temporary support, and embedment placement, and various types of lifting equipment. In reality, however, variations on erection sequence and rework are unavoidable. Therefore, the erection subcontractor totally relies on the general contractor's instructions to proceed every lift and wield. As a result of eminent necessity during the erection stage, the subcontractor is usually paid by man-hour at a premium rate whenever its workforce is on site. For contractual risks, the general contractor will carry the majority of them, whereas the subcontractor is nearly risk free. For the quality assurance of wielding, some non-destructive testing is done in situ by a nominated third party at the general contractor's own cost.

Finishing of Components Connection

This portion of the structural construction usually produces the majority of precision discrepancies. Since the finishing tasks are only applicable to component connections and surface waterproofing treatments, the work volume of each specialty is considerably lower than what is usually seen in traditional methods. As far as subcontracting is concerned, contractual elements remain unchanged comparative to traditional construction subcontracts. One thing which should be noted is that the unit price of each specialty will usually increase due to the dramatic quantity reduction.

4. CASE STUDY AND DISCUSSION

To further examine the impact of the employment of automation technology on conventional subcontracting practice, two case studies (Chen, 1993) are reviewed here for two purposes, which are (1) the examination of the risk sharing nature, and (2) the comparison of cost structure when the prefabrication technology is employed. Again, the focus of discussion will be on the construction of the structural portion.

The Risk Sharing Nature

The risk sharing mechanism between the general contractor and its subcontractors depends on the contractual options which bind the parties into a framework of responsibilities. From the cases examined in this study, the general contractor basically transfers full component manufacturing responsibilities to the prefabrication subcontractor, as depicted in Figure 2a. The general contractor performs quality inspection when components are transported to the construction site. From then on, it assumes full construction responsibilities until the completion of construction. Such division of responsibilities as well as risks reflects the fact that, given that the general contractor does not own the prefabrication facility, it is in fact for both parties to be better off if the general contractor does not interfere with the prefabrication of components, provided that it provides complete and timely detail design information to the subcontractor. Indeed, such a balance of risk sharing is quite delicate and relies heavily on a "reasonable" pricing system in the subcontract.

If the pricing system in the subcontract is not well designed due to, for example, bounded rationality or unexpected events, the general contractor's risks will increase drastically, as shown in Figure 2b. It is forced by the main construction contract to assume the full construction responsibilities. Most critically, it is required to provide detail manufacturing specifications to the prefabrication subcontractor based on the detail design drawings and specifications. In other words, the completion of the detail construction information is jointly executed by the architect, the prefabrication subcontractor and the general contractor, whereas the general contractor has the risks of being given incomplete or late design information by the architect. A similar situation also exists in the erection and assembly of prefabricated components. Quite obviously, when disputes arise, the general contractor does not have too much room to negotiate with the prefabrication subcontractor, since it is locked by some particular component design which only that particular subcontractor has full knowledge of it.

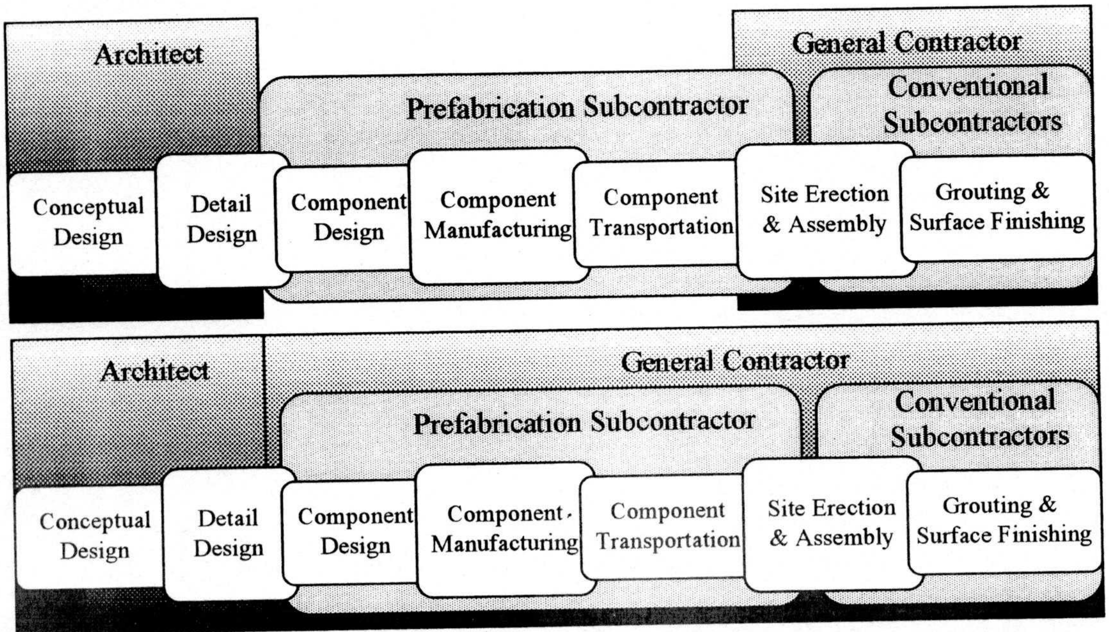

Figure 2 (a) The General Contractor's Responsibility from its Own Viewpoint
(b) The General Contractor's Responsibility from the Owner's Viewpoint

<u>The Cost Structure</u>

The cost structure of prefabrication is shown in Figure 3. Consistent in two case studies, the component prefabrication item consists of the majority of the construction cost. Clearly, the reliance on labor on site has been greatly reduced, but conventional subcontractors are still needed in the final finishing stage. The building technology used in Case 1 is SRC structure and the cost per unit area is 5% more than that of the conventional SRC construction method. The building method used in Case 2 is RC structure and the cost per unit area is close to 20% more than that of the conventional RC construction method. The cost increase in both cases is due to the fact that the prefabrication subcontractor's production planning is difficult to reach economies of scale. Out of 384 units in Case 1, there are three different designs, in that 50%, 33% and 17% of them each share a unique design. In Case 2, on the other hand, all units have the same design but only totaled 132 units. Under such a limited production scale, it is more costly to employ the prefabrication method.

It should also be emphasized that, except for component prefabrication, the other three main cost items are generally constant in terms of cost per unit area. If any attention is paid to reduce the construction cost, the focus should necessarily be put to component prefabrication. However, if the prefabrication plant is not owned by the general contractor, such an opportunity may not exist, even though the quantity of prefabricated component increases. Two governing forces are the demand-supply mechanism in the prefabrication market and the complexity of pricing system as presented in Table 2. If the demand for prefabrication is high (a seller's market), prefabrication may become even more costly. To the contrary, in a buyer's market, the general contractor may find prefabrication less expensive. In both circumstances, the general contractor may still be paying more than it should due to information impactedness and small number transactions (Williamson 1991).

Another notion can be observed from Figure 3 is concerned with the general contractor's subcontracting practice. Since prefabrication alone consists of an average of 70% of the construction cost, the arrangement of the contractual risks becomes much more critical than that in other subcontracts. In order to control cost and schedule, it will be necessary for the general contractor to specify clearly the date and quantity of different sizes, shapes and embedments for each components delivery. Apart from supervising work on site, the general contractor can only rely on sophisticated material management and quality control system to ensure the prefabrication subcontract is not breached. Therefore, this particular subcontract is seemed more close to a spot transaction to the general contractor, similar to the procurement of concrete or rebars.

5. CONCLUSION

Conventionally, a building constructor will assume the role of a general contractor and sub out the construction work to subcontractors in order to transfer construction risks and control cost. Through subcontracting, the general contractor can then minimize its capital investment and the employment of permanent personnel. As labor shortage, especially the lack of skilled workers, becomes an epidemic problem, adopting automation technologies provides vast opportunity for a constructor to remain competitive while profitable. In turn, the employment of automation technologies impacts domestic subcontracting practice in various aspects. This paper spends substantial effort in discussing such an impact thru two technological extremes, i.e., a single-purpose automated equipment and prefabrication. In both cases, it is shown that the complexity of the subcontract increases enormously. Most importantly, it is difficult for a general contractor to maximize its benefit of using automated construction methods, as itself alone does not control the "know-how" and the related action of producing the benefits. This is quite contrary to conventional construction methods in which the general contractor can easily obtain technical and pricing information from numerous subcontractors. This new situation has two implications to the general contractor. First it will have to assume most of the construction risks, and secondly a "reasonable" pricing of subcontracting is determined largely by the market rather by itself. From the case studies on prefabrication, it is also seen that a prefabrication subcontract resembles the characteristics of a procurement one, only much more complex. This leads to more emphasis on procurement and material management but less on site work. To most conventional general contractors, this will have a major influence on their internal organization. An additional observation underlined is concerned with the relationship between the general contractor and the prefabrication subcontractor. Since prefabrication consists of 70% of the total construction cost, it is logical for a general contractor to devise special relationship with the subcontractor such as joint venture, vertical integration or even internalization. For both cases examined in this paper, this inference is verified.

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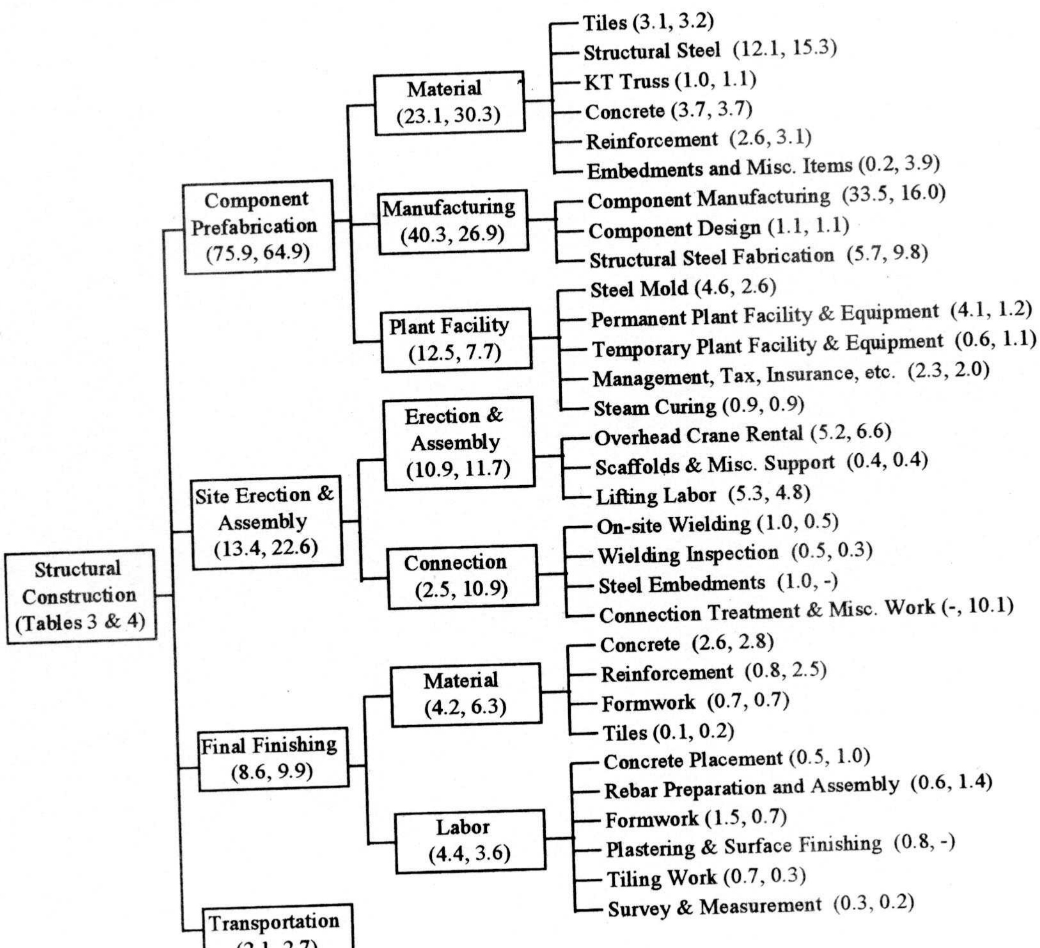

* Numbers shown are the percentage of the total construction cost, in that the first numbers in the parenthesis are those of the Case 1 and the second numbers are those of the Case 2.

Figure 3 The Cost Breakdown Structure of Prefabrication Construction