Accounting for transport times in planning offsite shipment of construction materials

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Abstract

Offsite transportation of construction materials is planned commonly by considering the transportation costs as the dominant decision variable, while transport time is of major concern usually in planning procurement stage of long lead items. Accounting for the off-site material transport time in planning of projects is particularly important in mega industrial projects where small delays in activities requiring diverse materials could impede the progress of projects and create damages of thousands dollars. This paper proposes a model to estimate the duration of offsite transportation in mega industrial projects through categorizing construction materials based on their supply chain structure as well as accounting for the effects of transport mode, size and weight of consignments. The correlations between delay in delivery of materials and a number of influencing parameters including material category, size, weight and mode of transportation were investigated using the data from two industrial case projects. The importance of planning for off-site transportation was found to vary considerably depending on the type of the material and its successor activities. Moreover, manipulating logistics variables of each order can improve its transport duration leading to a reduced project delay. Nevertheless, this process demands for a vigilant case-by-case analysis.
Keywords: Planning offsite transportation, construction material categories, shipment variables, delay

Introduction

Contractors of industrial mega projects are increasingly engaged in supplying materials from diverse sources around the world. Statistics declare that more than 65% of a construction project budget is spent on procurement of materials (Scholman, 1997). On-time procurement of materials is crucial to ensure on-time completion of construction projects (Abd El-Razek et al., 2008; Al-Momani, 2000; Fallahnejad, 2013). In particular, delayed procurement of materials may influence the process of managing material-intensive tasks in which the stock level is a vital factor for maintaining the smooth flow of work. Ensuring the on-time delivery of materials is, however, challenging and requires planning, monitoring and control of different stages of the supply chain including the transportation stage (O'Brien, 2008).

Off-site transportation of materials has been estimated to account for 10% to 20% of the total project expenditure in typical industrial construction projects (Shakantu, 2003). A great deal of research has been conducted to minimize the material procurement costs through optimisation of the transportation stage (Irizarry et al., 2013; Said et al., 2011; Tserng et al., 2006). However, little has been done to investigate the effects of the off-site transportation stage on the duration of construction projects and to develop systematic methods for estimation of duration of the off-site transportation stage in the material procurement process.

The existing literature on planning off-site transportation is limited mainly to investigating the effects of lead time of bulk materials on the duration of the corresponding activities (Ebrahimy, 2010). In industrial and infrastructure construction projects, however, planning delivery of long lead items has grabbed the most attention (ref.) and the common perception of industry implies that planning of the off-site transportation stage is usually of major concern when dealing with long lead items (Ahmadian et al., 2014); whereas researches on
causes of delays in construction projects frequently pinpoints late delivery of material as one of the main causes with no distinction between different types of materials (Ref.).

On the other hand, many activities, including critical ones, require a diverse range of materials and late delivery of any of them could impede progress rate of project leading to extended project duration. Therefore, to improve scheduling process of a construction project it is important to know how much delivery stage of different materials can contribute to project delay and how effective planning of transport stage could be for a timely delivery period.

The effects of basic physical characteristics of materials including size and weight as well as logistics variables such as mode of transport on duration of off-site transportation of materials in industrial construction projects have not been adequately investigated. Furthermore, there is a lack of systematic approach to evaluate the effects of such parameters in the planning stage (Ebrahimy, 2010; Irizarry et al., 2013; Said et al., 2011; Tserng et al., 2006).

This paper presents a conceptual framework for estimating the duration of off-site transportation of construction materials. The proposed framework mainly focuses on two objectives:

- First, to realistically estimate transport duration through predicting delay associated with each material supply chain structure and characteristics of consignments including size, weight, and mode of transport, followed by updating the project plans according to the estimates made.

- Second, to manipulate those variables to reduce shipment period of items and improve project overall duration as a whole.

The existence of strong correlation between different material characteristics and transportation duration, which is the basis of the proposed framework, is validated using the results of a case study. The data received from two industrial construction projects are
examined statistically to investigate the effects of material type, mode of transport, size and weight of each consignment on the duration and efficiency of shipment process. Also, the application of the proposed model in manipulating logistics variables to improve project scheduling practices and to reduce delay is shown.

The findings of this study are applicable to planning off-site transportation of construction materials for mega industrial or infrastructure projects in which thousands of diverse items should be procured from different overseas sources. Traveling under multiple transport modes, each mode constrained with their own limiting conditions, is an evident feature of materials transport phase in this type of projects.

**Literature review**

**Transportation phase and supply chain management**

The current practice in the construction management field for developing the supply chain is to optimise the overall process by considering the cost trade-offs between three main components of the chain; i.e. transportation, inventory, and production (O’Brien, 1998). A number of previous studies have focused on developing cost effective approaches for logistics and shipment strategies. Irizarry et al. (2013) used an integrated Building Information Model (BIM) and Geographic Information System (GIS) for logistics management in the supply chain of construction materials. A model was proposed to find the optimum strategy for transportation of materials, from a supplier to the construction site, in terms of number and time of orders, order quantity, transportation methods, and the associated cost of transportation. This work was, however, limited to local supply of building materials in one state in the US using road transportation. Furthermore, the transportation duration was not considered as an interdependent variable in the trade-offs considered.

There is generally an interdependent relationship between costs and duration of material transport stage. Due to the importance of costs and time as direct objectives of projects, both
these factors should be used as decision making criteria for selection of the optimal transportation strategy in a particular project. In most situations, however, the transportation duration alone may be able to provide an insight into the efficiency of the transportation strategies (Wegelius-Lehtonen, 2001). Furthermore, the monitoring of the time, for logistics management purposes, is easier in practice than monitoring of costs (Towell, 2009). On the other hand, the time records tend to be generally more accessible in practice than the costs data. The accessibility to adequate information is a key to successful implementation of any process (Davenport, 1995). By taking into account the above discussion, the use of time as an indicator of status of operation, instead of costs, to provide feedback on the material delivery process is more likely to be realized in practice. In this regard, the communication and information technologies may play a crucial role in providing real time data on material delivery process (Omar and Ballal, 2009; Williamson et al., 2004).

**Delivery strategy and governing rules**

In international trades, transport of goods and materials between sellers and buyers requires several decisions to be made. One of the important decision variables in planning of transportation stage is the mode of transport which is usually selected based on the results of a trade-off analysis between cost and duration of delivery (Leesor, 1996). Apart from mode of transport and terms of delivery, speed of shipment is also subject to limitations enforced by relevant authorities. Depending on weight and dimensions of consignments, guidelines recommend certain limitations on the speed of the transportation vehicles (Ceuster et al., 2008). Such rules are implemented usually to ensure safety of the environment, other transportation system users, and the operating crew and to preserve the pathways operational. The guidelines may vary considerably from a territory to another depending on factors including traffic capacity, load allowance of bridges, and width of roads (Ceuster et al., 2008; Luskin and Walton, 2001). A systematic transportation planning approach should take these
restrictions into account in estimation of the transportation time for different construction materials (Vrijhoef and Koskela, 2000).

Material classification for transportation planning

From a construction industry point of view, classification of materials is commonly based on the lead time. In this classification, materials are grouped generally into two categories; critical items and noncritical items. Critical items, also referred to as long lead items in construction planning, are usually building blocks of a system or a major equipment for which “the time to design and fabricate is the longest” (The Dictionary of Construction). On the contrary, noncritical items comprise materials with relatively shorter supply chains periods.

Manufacturing industry takes a different approach toward defining material classifications. This approach tends to be in line with the conventional objectives of manufacturers including increasing the competitiveness and versatility in the market and maximising the profit through reducing inventory costs (Gosling and Naim, 2009). To reach these objectives, a balance between production of customised products and standard items should be achieved. The decision made by a manufacturer on the structure of a supply chain may considerably influence its inventory management strategy. The inventory costs for production of customised items are generally lower than that of standard items (Demeter and Golini, 2014). In contrast, standard items demand for more storage capacity. Therefore, manufacturers are inclined to dispatching standard items as soon as possible to reduce the inventory costs (Chikan, 2011).

Although different methods are available to categorize materials in a production system, such methods are mainly based on a common concept known as “decoupling point”. This concept classifies supply chains based on the proximity of the point at which they respond to the customers’ demand (Christopher, 2000; Olhager, 2003). The categorization methodology
proposed by Olhager (2003) is perhaps the most recognised material categorization method
used by the manufacturing industry. This method divides materials into four non-overlapping
groups including made-to-stock (MTS), assembled-to-order (ATO), made-to-order (MTO),
and engineered-to-order (ETO) products (Olhager, 2003; Babu, 1999). For MTS materials
decoupling point is at the shipment stage. However, for ATO products, this point goes farther
into the production stage and may possibly occur as late as sometime in the final assembly
stage. The decoupling point of MTO products is usually in the fabrication and procurement
stage. For ETO items, this point is generally as early as in the design phase (Olhager, 2003).
These four categories of products are usually prioritized based on the longevity of their
supply chain as ETO, MTO, ATO, and MTS, respectively (Tommelein et al., 2008).

The difference between construction and manufacturing industry with regards to material
supply chain management is not limited to the categorization process. There is also
considerable difference in their perspectives in the way bottleneck is identified. Identification
of the bottleneck stage is especially vital to successful implementation of time compression
principles. Manufacturing industry takes a systematic approach to identifying bottlenecks
based on the materials categories defined. Elfving et al. (2005) identified the design phase as
time blockage of the ETO supply chain. For MTO materials, detailed engineering phase has
been recognised as the time-consuming step (Laitinen, 1993). On the contrary, the transport
stage of construction materials has not been studied explicitly as a time bottleneck. The
impact of the lead time of bulk materials on duration of construction activities was
investigated by Ebrahimy et al. (2010). They proposed an equation to estimate the minimum
duration of a task using the lead times of materials necessary to undertake the task. Although
the proposed formulation accounts for the transport time in estimating the duration of a task,
no discussion was presented on the methodology adopted for estimation of the transport time.
In general, there is a lack of literature on planning of transportation phase of the supply chain and its importance in the procurement process in terms of time. This mainly originates from the existing perception that the impact of the transportation stage in construction projects is insignificant and any problem associated with the transportation of construction materials is in fact a consequence of another problem in the previous steps of the supply chain (Laitinen, 1993).

However, it is not the case in all circumstances and for all types of materials. As some categories of material like those falling in MTS or ATO category have a straightforward supply process with short lead time before their shipment, their transport stage could become a bottleneck if not sufficient planning is done. Even if their proposition is accepted, a timely or even shorter transport period gets higher importance when pre-shipment stages are vulnerable to delay. This is particularly vital in mega industrial or infrastructure projects in which a great proportion of items have to travel across different territories under multiple modes of transport each of which with their own limiting conditions.

Therefore, a framework that can appropriately take period of transport stage for different construction materials into account of project scheduling is essential.

**A holistic model for off-site transportation**

The proposed framework for planning the transportation stage of materials with the objective of minimizing the delay and its associated economic impacts in projects is shown in Figure 1(a). The proposed framework is especially designed for long term construction projects, typical of mega industrial projects, where replanning based on feedback from monitoring of performance in early stages of project may be used to reduce considerably the risk of delay in the later stages.

The proposed framework comprises seven stages. The planning starts by categorizing materials into ETO, MTO, ATO, and MTS groups according to the methodology proposed by
Olhager (2003) (Stage I). The project team then decides on the mode of transport, size, and weight of consignments that are believed to influence the transport duration (Stage II). In the next stage (Stage III), historical data, from previous similar projects or early stages of the current project, are studied. For each material category, the correlation between the delay in transportation relative to the planned duration, experienced in previous similar projects, and different physical characteristics and logistics variables including size and weight of consignment, mode of transport and lead time are investigated (Figure 2b). A series of regression models are developed to estimate the potential delay in transportation of each category of material as a function of consignment characteristics and mode of transportation.

In the next stage (Stage IV), a rough estimation of the transport duration of each material required for the current project is made. In this stage, depending on the availability of data, two different approaches may be taken i) if data on correlations between above-mentioned influencing parameters and transport time in previous similar projects is available, such correlations (as identified in Stage III) are used to make the initial rough estimates. ii) if no or insufficient reliable data from previous similar projects is available to identify correlations, the initial transport duration estimate is made using the ratio between transport duration and total supply chain duration of respective materials in previous projects. In stage V, which is an ongoing stage throughout the project, the delay in transportation is monitored and recorded continuously and linear regression models, developed previously using historical data, are updated. In the next stage (Stage VI), the effects of potential delay in the delivery of materials on the start time of the succeeding activities in the project schedule is examined. In such cases, if the anticipated delay with respect to initial travel time estimates is more than the existing slack for transportation activity, replanning will not be required. On the contrary, in case the start of succeeding activities is affected by delay in delivery of components, additional analyses will be required prior to modifying the project schedules. This should
include appraisal of the potential costs incurred due to the delay in construction activities caused by the delay in the transportation phase. The economic appraisal of impact of delay together with economic, contractual and managerial implications of changes to the existing plan should then be used as criteria in a multi-attribute decision analysis to select the best replanning strategy (Stage VII). The alternative re-planning strategies considered may also include changes to the mode of transport, size and weight of orders to achieve a shorter shipment phase.

When considering the costs as the primary decision criteria, a comparison between the expected delay cost and additional logistics costs will determine how to proceed with either of the following directions: i) if the delay costs are less than the additional costs created by the change in delivery variables, project team may accept to postpone the project completion date and reject such variations, ii) larger contractual damages can justify the decision on modifying the transportation factors for an earlier arrival of materials at the construction site.

**Case Study**

The existence of strong correlation between different material characteristics and transportation duration, which is the basis of the proposed framework, was validated using the results of a case study. The projects were intentionally selected from oil-refinery construction projects in which considerable amount of materials and components are fabricated offsite and shipped to the construction site.

The scope of the first project is revamping and expansion of an existing oil refinery, while the scope of the second project is construction of a new gas refinery. Both projects are located in the same region in the Middle East and have the same owner. These projects are currently in the construction phase. Despite being undertaken by different contractors, the required materials for both projects are procured from the same group of approved
international manufacturers and suppliers. Therefore, the shipment data of procured items were combined and analysed as one set.

According to the information extracted from databases of projects’ control office, completion of these projects requires the procurement of more than 3500 diverse items which can be classified into structural, mechanical, piping, instrumentation, and electrical groups. The total number of consignments (each including multiple items) delivered to the construction sites by the time of this study was 149. Table 1 summarizes the characteristics of the shipment packages in terms of weight, dimension, and trade condition of delivery. Mode of transport has not been reflected in the table, as each item experienced more than one mode during its trip to the job site.

**Duration of transport stage in the supply chain**

Evaluation of the original schedules and discussions with project managers of case projects revealed that the planned transportation durations, from vendors’ shop to the final destinations, were estimated initially as a proportion of the overall supply chain duration. The ratio of the planned transportation duration to the total procurement duration was found to vary from 10 to 20% for the majority of items depending on the distance. In this study, the overall procurement duration is considered as the time period between placing a purchase order and the arrival of purchased materials at the construction site. However, analysis of recorded travel time data showed that depending on the material procured, the actual ratio between the duration of transportation and the total supply chain duration varies from 2 to 70%, indicating considerable deviations from the planned travel time durations. The considerable variations in the ratio of actual travel duration to the total supply chain duration for the different materials implies the existence of a diverse supply chain structure for the construction materials procured and highlights the need to account for such a diversity in the planning stage. With this in mind, the materials required by the case projects were
categorized into ETO, MTO, ATO, and MTS classes as proposed by the framework presented, to investigate the potential correlations between the recorded delay in the transportation duration and various characteristics of materials. Table 2 summarizes the main attributes of each material category along with the examples of items belonging to each category in the case projects considered.

As can be seen in Table 2, ETO materials include boilers, customized compressors and pumps, large-size control valves, pressure vessels and some steel platforms. Fabrication of such items requires considerable design effort, a great deal of communication between engineering firms and manufacturers’ workshops, and procurement of a diverse range of materials from different suppliers. In general, such components are proprietary products of suppliers and their know-how is confidential. On the other hand, a wide range of pumps and compressors, medium to high pressure tanks, medium-weight steel structures, medium or small-size control valves, and temperature and pressure control instruments, which require generally a less technologically sophisticated production process, are assumed as MTO items. ETO and MTO components are normally ready to be installed and connected to their surrounding items in the plant with minimum further fabrication efforts at the jobsite.

Pipe spools, low weight steel structures, low power electrical motors, low rating heat exchangers, temperature and pressure gauges, and small atmospheric tanks are considered as ATO. ATO items generally need to undergo a number of prefabrication steps at the job-site before their installation. All other standard materials including bolts and nuts, steel sheets, elbows, hand valves, cables, small size pipes and tubes are samples of MTS components. MTS materials are essential accessories that contribute into completion of almost every construction task.

The relationship between actual duration of transportation and the total supply chain duration was examined for each material category. As shown in Figure 2, the results of
analysis indicated a statistically significant link between the transport duration of MTS and MTO materials and the total duration of supply chain with adjusted $R^2$ equal to 0.54 and 0.75, respectively. However, a different trend was observed for ATO and ETO materials.

Comparison with the actual transportation duration revealed that the initial estimates for the shipment duration of ATO and ETO materials based on the total time of supply process were generally inaccurate. The reported impacts of the delays caused by material delivery issues have been summarized in Table 3. The authors have extracted this information from a report entitled “Schedule Delay Analysis-using SNAPSHOT technique” released by the projects team. This report details projects’ delays in an Activity Breakdown Structure (ABS) format in which causes of delay and their corresponding delay amount is linked to each construction activity. For the purpose of present study, activities were divided into different criticality groups based on the amount of total float available. Accordingly, the percentage of delay attributable to material delivery, as shown in Table 3, is calculated by normalizing weight of material related delays in each criticality group defined through the ABS format. Moreover, the minimum and maximum impact of materials delays on the overall projects duration is automatically estimated in this spreadsheet format.

On the other hand, the authors applied their suggested material categorization method to understand how each material category and its transport stage contribute into occurred delays. Subsequently, contribution of each material category in causing material attributable delays is stated as a percentage and is obtained from normalized weight of delay in each material category versus total delay caused by materials in that activity group. Table 3 also shows the duration of the transportation phase relative to the duration of the supply chain for each material category which is independently calculated through available transport data on each order in comparison with its total supply chain duration.
As shown, the results of this analysis specially highlight the importance of precise planning of transportation phase for procurement of the MTS materials. The importance of shipment stage for MTS components is twofold. First, the duration of transportation accounts on average for 50% of the total MTS supply chain duration and may be considered as the most dominant phase of the supply chain in terms of time. Second, any delay in delivery of MTS items will adversely influence the progress rate of critical activities, leading to the late completion of them. In contrast, contribution of transportation stage to the late delivery of ETO materials at the construction site seemed to be insignificant and the main causes of the delayed delivery of ETO materials pertain to their pre-shipment phases.

The value of accurate transport planning for ATO items varies depending on the proximity of the supply source and float of the successor activities. As shown in Table 3, the transportation duration of ATO materials may be a matter of concern only if its contribution to the overall supply chain duration is significant (i.e. for long transportation distances) and the float time of succeeding construction tasks is inadequate to the compensate for the delay in shipment. On the other hand, the transport stage of MTO materials was shown to have a limited contribution to time efficiency of the supply chain process and did not exceed 20% of the overall supply chain duration. The significance of timely shipment for MTOs may increase when its predecessor activities are highly likely to be delayed, e.g. in case of delay occurrence in manufacturer's site, leading to availability of no or little float for delay in the transportation stage. This is mainly because the potential transportation delay is not usually factored in scheduling of construction activities and the majority of construction activities are planned by considering a limited float to accommodate the potential delays caused by a wide range of other factors, leaving little room for delays in the supply process.

**Transportation delay and its associated variables**
Mean values for the average delay of items in ETO, MTO, ATO, and MTS material categories are 1.2, 5.84, 10.31, and 12.7 days, respectively. While accounting for material classification improved the accuracy of the travel time estimates, considerable differences seemed to still exist between transportation duration estimates and the actual transportation duration records of case projects. This suggests that transportation duration is influenced by more parameters than material type alone. By taking this into consideration, the relationship between delays occurred in each class of materials and characteristics of consignments, in terms of size, weight, and mode of transport, were examined.

**MTS materials**

Table 4 summarizes the results of a statistical analysis performed to evaluate the relationship between delay during the transportation phase of MTS materials and characteristics of consignment including mode of transport, size, and weight of orders. The dependency on distance was initially normalised by dividing the delay values by the distance of the shortest trip required in the case projects (2500 kilometres). As shown, a relatively strong correlation was observed between delay and the independent variables corroborated by an adjusted R square value of 0.474. Moreover, the magnitude of the estimated coefficients reveals that weight has a greater impact on delay rather than dimension and mode of transport. The greater coefficients obtained for heavier carriages suggest that magnitude of delay escalates with an increase in the weight of consignments. At the same time, the effect of size on delay of MTS items seemed to be insignificant and only small size packages experienced delay during their trips. In terms of modes of transport, marine and railway transportation were found respectively as the most reliable modes in terms of reducing the risk of delay.

To verify reliability of linear regression analyses performed on the transport data, it is a common practice to predict delay on each individual consignment using coefficients of significant variables in its corresponding category. Then, a comparison between the predicted
delay and the actual delay is made on all items of each category via a graph, as shown in Fig. 3. At the same time, distribution of differences between forecasted and actual delays is also drawn, as Fig. 4 indicates. Then, reliability of the performed statistical analyses on each category can be approved if $R^2$ of its relevant diagram in Fig 3 is equal to or greater than its previously found adjusted $R^2$ in its regression model, and a corresponding normal distribution of errors for the category is observed in Fig. 4.

As such, by considering the coefficients of different variables shown in Table 4, the following equation may be derived for prediction of delay (with regards to estimates made based on lead time and distance) in delivery of MTS items:

$$D = 2.62 + 1.21 \times M + 1.97 \times H + 2.78 \times SH + 0.71 \times S - 0.88 \times W - 1.42 \times V$$

where $D$ is delay in days per each 2500 kilometres of the route; $M$, $H$, and $SH$ represent medium, heavy, and superheavy packages, respectively; $S$ is small size orders; and correspondingly $W$ and $V$ are railway and marine modes of transportation. Figure 3(a) compares the delivery delays predicted using Equation 1 and the actual delays observed for each consignment during the course of the project. The distribution of the error between observed and estimated values, shown in Figure 4(a), verifies the importance of considering the characteristics of items in precisely predicting the transportation delay. In other words, a bell shape normal distribution is obtained for the error term which confirms the assumption that the error is normally distribution. Therefore, dividing MTS orders into lighter packages and selecting routes that include longer sea and rail paths than road paths can reasonably decrease the relative duration of transportation. In fact, while transportation of lighter packages by road allows for a higher vehicle speed, sea and railway may be considered as paths with less traffic and more reliable shipment timetables.

ATO materials
The wide range of ATO materials from diverse sources made it difficult to make general conclusions about the effects of various item characteristics on their transportation time. Nevertheless, statistical analysis of shipment data showed a moderate correlation between delay and some of transportation characteristics. Table 4 indicates an adjusted R square value of 0.369 for the goodness-of-fit of the delay model as a function of weight and mode of transport. The highest values of delay were observed to be associated with heavy consignments. Moreover, air transport was identified as the best mode of transportation to reduce the transport time, subject to its practicality. On the other hand, road transportation was shown to play a more explicit role in delay of ATO materials than MTS items. However, ATO seemed to resemble MTS in lack of significant correlation between size of orders and the delay in the arrival of shipments.

The coefficients of significant variables presented in Table 4 were used to derive a model to predict the delay in delivery of ATO materials. Figure 3(b) compares the delay predicted using the latter model with the actual delay in delivery of ATO consignments observed during the project. Despite the diversity of ATO materials, reasonable agreement exists between predicted and actual delays (Figure 4(b)). In a trend similar to that observed for MTS items, lighter ATO packages seemed less likely to experience delay in transportation and road transportation was identified as an important phase contributing to the delays. Not surprisingly, the results of analysis indicated that air transport can be used as a rapid alternative for sea lines to carry some of packages in this category of construction materials, again subject to feasibility of this mode of transport.

*MTO materials*

The results of the statistical analysis of the relationships between various materials’ characteristics and duration of transportation of MTO items, which constitute the biggest category of construction materials, are summarized in Table 4. As shown, the regression
model representing the relationship between consignments’ characteristics and transportation duration showed an adjusted R square of 0.593. While air transport and large size consignments were observed to positively influence transport duration and reduce probable delay, the use of road trucks was identified as the main bottleneck for the delivery of MTO items. The prediction potential of the corresponding regression model is presented in Figure 3(c). As can be seen, the predicted delay values are associated with minor errors in the majority of cases. Therefore, the regression model can be used as a reliable framework for decision making about logistics characteristics of MTO orders with acceptable error values (see Fig. 4(c)).

Unlike ATO and MTS materials, shipment size appeared to be a determining factor in the duration of MTS components while unexpectedly bigger size items take shorter time to be delivered to the construction site. This could originate from the limited quantity of items included in each big size MTO package. The latter may reduce the time required for handling process including loading and unloading, counting, inspecting, and handover of materials. On the contrary, a more tedious and time consuming handling process is usually involved in transportation of thousands of individual pieces in ATO and MTS consignments. Table 4 also shows that the greatest coefficient of variables in this category of material belongs to road. This may be explained by the fact that dimension of MTO items can be a limiting factor in road transportation where road restrictions such as width and traffic congestion can lengthen travel time.

ETO material

The transportation duration of ETO materials was close to the planned duration for majority of items. Except two orders which experienced slight delays during shipment, the rest of packages were delivered on or earlier than expected delivery dates. This contradicts the common perception about the supply chain of ETO items or long-lead items. Based on the
projects’ records, although seven out of 13 orders were significantly delayed, such delays were related mainly to phases prior to shipment process.

A short paragraph probably will be added after receiving your comments on the next section, to integrate the results of all analyses and their limitations.

**Application of the model to improve schedule**

To demonstrate how the proposed model can be used in improving current practices, Table 5 indicates a series of corrective actions taken by the project team to influence timely delivery of sixteen purchase orders needed to complete construction activities with higher criticality in a three-month timespan of the projects, apart from 149 orders previously arrived at the construction sites. These orders were among 41 orders that had been planned to arrive at the construction sites in that time period, even though late arrival of 25 items were identified as delays with minor effects on project end dates and just led to a schedule update based on improved estimation of their transport time.

The corrective actions appear as changes on characteristics of those items and every change decision was subject to criticality of relevant successor activities, practicality of change and a quick trade-off between its effects on project overall cost and duration. Six typical changes implemented by the projects team to possibly improve delivery period of orders range from purely logistics modifications; like adaptation between size and weight of orders (leading to either size or weight decrease), splitting consignments (leading to both size and weight decrease), mode of transport, and route; to higher-level decisions including source of origin and supply chain structure. Although the authors were not informed about reasons behind higher-level changes, it is evident that such changes may concurrently impose some logistics change.

To assess how those changes comply with the results of this study, first the authors used the derived regression models to estimate delays associated with each consignment before
any change. Then, we independently assumed all practical changes in logistics variables of each order based on the derived regression models with no consideration of their associated costs. Subsequently, an equivalent range of delay reduction on each consignment is calculated in which minimum value represents impact of the least effective change on transport stage and maximum value indicates collective outcome of the whole possible changes on the order’s characteristics. Finally, a comparison between the effects of changes considered by the authors and implemented changes by the projects team reveals the effectiveness of the proposed methodology.

Table 5 gives similarities and differences between the changes considered by the authors and those implemented by the projects team and compare their impacts. As shown, majority of the changes implemented by the projects team are in agreement with the authors’ speculations, (denoted by “√”). Yet, a quarter of the authors’ change ideas, denoted by “×”, had not been implemented in the projects. Moreover, changes indicated by “˄” are those that had been executed beyond guess of the research team either because of their knowledge or their available information.

Two items were excluded from the assessment. One is an ETO as the transport data on past ETOs doesn’t show a significant delay and no statistical model was available to assume any change. Second one is an ATO item (no. 8) in which its condition had left small room for delay improvement.

By excluding items where additional changes (“˄”) had been executed, the projects team on average has reached 66.7% of the maximum expected delay reductions by implementing majority of the proposed changes in compliance with the model. These achievements in MTO, ATO, and MTS items are 46.7, 61, and 71%, respectively. This trend is in contrast to the highest adjusted R-square of regression models which belongs to MTO materials. On the other hand, delay reduction achieved in MTS and ATO items show a wider range than ATO.
Therefore, these reveal limitation of the regression models which were made on available data and its implication is twofold. First, the low delay improvement achieved for ATO items necessitates inclusion of other factors to enhance quality of the proposed framework. Second, the wide range of improvements achieved on MTS and ATO highlight the need for a bigger sample to conclude about them.

On items with higher-level changes a mixed outcome is observed. While an improvement of up to 100% proved to be achievable in items by both implementing logistics and non-logistics variations, the lowest improvement of %11 belongs to the last item where two out of three model-based changes were rejected by the projects team.

As an ultimate result of all changes, projects team has claimed that schedule updates before and after implementation of all the changes indicated a decrease between 47 to 69% in projects overall delay caused by those items. Overall, the changes and their effects illustrate a satisfactory level of agreement with the findings of the regression models and the proposed framework for incorporating variables including material category, size, weight, and mode of transport to improve planning delivery of construction materials for a smooth construction process. However, when modifying orders’ variables cares need to be exercised with regard to category of material, practicality of changes, and added-value of changes.

Besides, implementation of a change rest on its added-value in the project as a whole. According to this fact, projects team have not implemented some of the possible changes on an order because they found their costs overweigh their value in reducing projects’ duration. Moreover, they have just accepted delay in items required for lower critical activities through updating schedules as no extension to the end date of projects was realized.

Overall, although category of each order in conjunction with its relevant statistical model direct decisions on type of changes, a case by case judgment process should be paved to determine details of changes for any consignment. In facts, moving toward reduced transport
duration highly depends on practicality of changes. In other words, project team has to examine:

- what current characteristic of an order are (weight, size, mode of transport, route) in a materials category
- how realistic it is to split an order or how size and weight can be made compatible with each other to increase travel speed,
- in which routes they can change mode of transport,
- and what alternative routes are available.

**Conclusions**

This research expands knowledge on importance of off-site transportation stage in improvement of construction scheduling practices from commonly long lead items to a more narrowed categorization of construction materials as well as incorporating logistics variables. To fulfil this, a framework for planning the off-site transportation stage in mega industrial construction projects was proposed. The proposed method makes use of a well-established material categorisation approach of the manufacturing industry to split the data in homogenous clusters. It also utilizes the characteristics of consignments including size, weight and mode of transport to analytically approximate the transportation duration for different material categories. The data collected from two industrial construction projects were statistically analysed to validate the existence of correlations between duration of transportation and material type, size, weight and mode of transport. Such correlations form the basis of the proposed framework. The results showed that delay in transport time of small standard items mainly falling under MTS category can have dire consequences on the project progress. This is because most activities in a project rely on availability of MTS materials. In contrast, shipment times of long lead items classified as ETOs do not play a significant role in their total supply chain delay. On the other hand, importance of precise estimation of the
transport stage for ATO and MTO items, which include a wide range of prefabricated
construction components, varies depending on the flexibility of their successor activities.

Statistical analysis of the shipment data for each category of materials indicated that
estimation of travel time can be improved through incorporating significant variables like
material supply structure, size and weight of orders, and mode of transport. Road
transportation was observed to be more prone to delay compared to sea and air modes of
transportation. The weight of consignment was found to be an important parameter affecting
the duration of the road transportation. This is because the road travel speed limit can be
affected significantly by an increase in weight of MTS and ATO categories. On the other
hand, the size of consignment appeared to be a more important factor than weight for
transportation of MTO materials where large or ultra-large equipment can turn road
transportation into a bottleneck due to traffic limitations. Air and sea transport were identified
as more reliable modes of transports especially when on-time delivery of items is critical.

To reduce delay in transport stage of construction materials, planned characteristics of
consignment can be manipulated considering their material category and its significant
variables. The decision to change such characteristics firstly relies on possibility of
implementing those changes. Secondly, project team examines added-value of each change
for the project to ensure its delay reduction benefits overweigh its costs. This analysis directly
depends on the effect of that material on the criticality of its successors.

Nevertheless, application of this framework is limited to using type of materials, size,
weight, and mode of transport in consignments for planning transport stage. Other influential
factors for a smooth shipment period including climatic condition across the route, custom
office process, and contractual condition of shipment have not been taken into considerations
because of lack of access to relevant data.
Moreover, as the chosen cases are oil industry projects located in a territory far from manufacturing and technology hubs, supply of diverse materials includes long overseas journeys in which many of orders have to travel under multiple transport modes. Therefore, specific statistical findings of this research may not be exactly applied to projects in dissimilar contexts in terms of both industry and territory.

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**References**


Figure Captions

Fig. 1. (a) The proposed framework for improving project schedule based on realistic estimation of transport time (b) improving transport time estimates using the historical data

Fig. 2. Actual duration of transportation vs. total duration of supply chain for different categories of construction materials

Fig. 3. Comparison between the predicted and the observed transportation delay using regression models

Fig. 4. Error distribution of the predicted delays based on regression models of significant variables for different categories of construction materials