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A BIM-BASED FRAMEWORK FOR MATERIAL LOGISTICS PLANNING

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ABSTRACT

Material logistics planning (MLP) is an important component of supply chain management that promotes tidy construction sites and efficient project delivery. It aims to ensure that the right materials and equipment are delivered to site at the right time so as to reduce the idle resources and space requirement on site. Therefore, MLP can support lean construction as it can reduce unnecessary transportation and material handling, which are regarded as waste. However, supply chain issues such as late or incorrect material delivery are still common on construction sites nowadays. This paper presents and demonstrates a framework based on building information modeling (BIM) for automated material logistics planning and management. Using the Revit Application Programming Interface, we developed a system framework that extracts geometric and material information from BIM models and integrates the information with schedule information for formulating a dynamic construction site layout model. Material delivery and storage information is made available to supply chain members for planning and monitoring purpose. Our framework also considers the interior space inside the buildings under construction, which is important for construction sites with limited available space. A case example is demonstrated to validate the framework and demonstrate its potential for construction management.

KEYWORDS

Automation, building information modelling (BIM), lean construction, logistics, site layout planning.

INTRODUCTION

Supply chain management (SCM) in construction projects has been studied in various research efforts (O'Brien, et al., 2002; Oakland and Marosszeky, 2006; Cheng, et al., 2010). However, an important but fairly less studied aspect of construction supply chain management is the material logistics and layout planning on construction sites, which deals with coordinating the material requirements of a construction site so as to minimize waiting time, double handling, and delays related to material deliveries. Thorough planning of the construction site layout, monitoring of site level activities, and continuous coordination with material suppliers is extremely vital in ensuring a

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well-coordinated material logistics plan (Pryke, 2009). Most studies on site layout planning use the planned construction schedule as a basis to determine – (1) the temporary facilities required for storage, (2) the time interval for which they are needed on the site, and (3) optimized locations for setting up facilities so as to minimize on-site transportation distances (Zouein, et al. 1999; Ma, Shen and Zhang, 2005). However, in most projects due to variations in construction times and supply chain uncertainties, the schedule undergoes modifications once construction progresses. As a result the site layout plan initially formulated around the construction schedule becomes unfeasible to implement. The site layout plan then serves only as a rough guide, with most of the governing decisions being made by the site superintendent. As a result, the planning effort is wasted and eventually leads to unplanned site layouts. In urban construction projects, due to the confined nature of the construction site, the site layout and material logistics plan have to be carefully coordinated in order to ensure a smooth workflow (Said and El-Rayes, 2013). Incorrect deliveries and stockpiling of materials on site lead to overcrowding of the workspace and can be seen as hazardous as well as contributing to operational inefficiencies. Large travel distances between material storage and installation areas, double handling of materials and overcrowding of the site due to improperly coordinated deliveries are common examples of operational wastes generated in urban construction projects due to a lack of planning (Said and El-Rayes, 2014). In order to facilitate lean construction, it is important to eliminate the occurrence of these inefficient practices. However, constrained site conditions, tight schedules and various material requirements of contractors make coordination of material deliveries an arduous task. The complexity of this problem is compounded with the addition of delays in deliveries and construction activities. In this paper we aim to develop a construction site material logistics system to aid in coordinating material deliveries on confined construction sites, thereby decreasing waste and supporting lean construction. Our framework addresses a key missing component of current material logistics systems, by addressing site layout planning not just on a strategic and tactical level, but also on an operational level. As a result the site layout can be properly coordinated with material logistics in order to facilitate lean construction.

Our framework consists of four modules - (1) construction progress monitoring module, (2) construction site space estimating module, (3) material delivery coordination module, and (4) material storage optimization module. By leveraging information from BIM models and construction schedules, we are able to automate several of the calculations required for our analysis. Material information is extracted from the BIM model and linked to the construction schedule to create a resource-loaded schedule. The resource-loaded schedule is used to estimate the consumption of materials, and forms the basis for planning the logistics of material delivery and storage. Another important feature of this framework is that it also considers interior storage spaces within the building under construction. In many urban construction projects, due to limitations in site space, materials and equipment may be temporarily stored on each completed floor of the building. In such cases it is extremely important to evaluate the storage requirements and availability ahead of time in order to avoid wastes associated with material double handling and conflicts with construction activities. The following four sections describe the framework in detail and also present a case example for validation.

THE BIM BASED MLP FRAMEWORK

The BIM-based MLP framework consists of four modules - (1) construction progress monitoring module, (2) construction site space estimating module, (3) material delivery coordination module, and (4) material storage optimization module.

CONSTRUCTION PROGRESS-MONITORING MODULE

A construction schedule defines the start and end dates of each activity comprising the construction project, thereby serving as a blueprint for the project. A resource-loaded schedule, in addition to activity starts and end dates, also contains information about the quantity of materials needed by each activity. It is important because it can tell us the quantity of materials that are required during different stages of construction, thereby serving as a basis for planning the material logistics of a construction site. Construction projects however, seldom stay on schedule, with many activities taking longer to complete than estimated. As a result, material logistics cannot solely be based on the planned construction schedule. The progress of each activity and its projected completion date must be evaluated before planning the material logistics. Delays in construction activities will otherwise result in excess materials being stored on site and may lead to site crowding or congestion (see Figure 1).

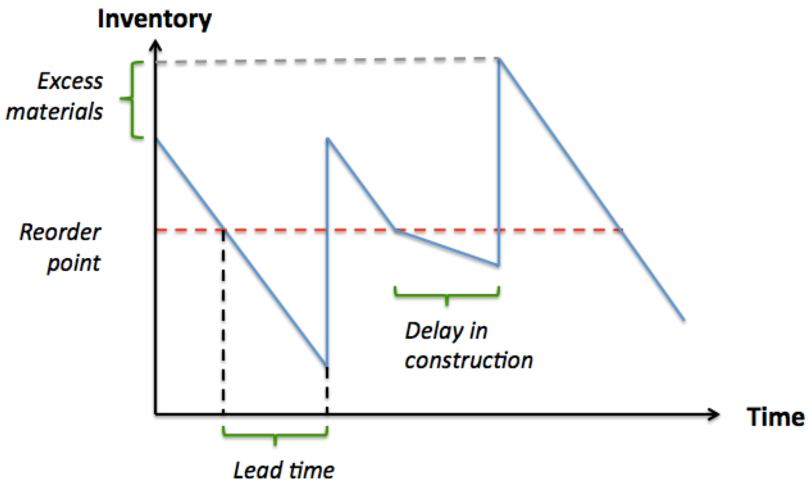

Figure 1: Delays in construction activities leading to excess materials being stored on site

As can be seen in Figure 1, delays in construction would result in a decreased rate of material consumption. Thus, in a given time interval, fewer materials would be consumed than was planned, leading to larger level of inventory. Construction sites with limited space may not be able to accommodate larger material inventories and as a result extra materials would have to be accommodated in temporary storage areas. In our study, the construction progress-monitoring module is used to estimate the progress of activities and estimate their completion dates. This can be done by breaking down each activity to terminal activities carried out on the construction site. Take for example the activity “1st Floor Column No. 01”, the activity associated with constructing a reinforced concrete column on the first floor. As shown in Figure 2, the activity can be subdivided into erecting formwork, arranging reinforcement, pouring concrete, curing and stripping off formwork.

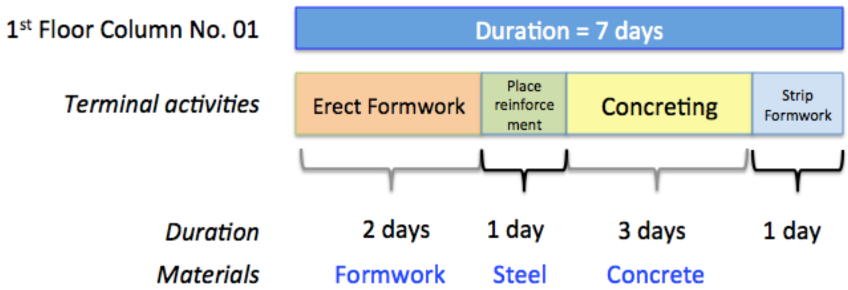

Figure 2: Splitting up of an activity into terminal activities

Our system requires users to input the status of each such terminal activity, on a daily basis. Based on the input our system calculates the delay in each terminal activity using the following equation.

$$t_{d,i} = t_{f,i} - t_{s,i} - d_i \qquad (1)$$

where $t_{d,i}$ refers to the delay, $t_{f,i}$ is the finish date, $t_{s,i}$ refers to the start date and d_i refers to the planned duration of the terminal activity i. A positive value of $t_{d,i}$ refers to a delay whereas a negative value indicates that the terminal activity is ahead of time. The delay in an activity is equal to the sum of the delays in the terminal activities that it comprises of, and can be calculated using the following equation.

$$T_{d,n} = \sum_{i=1}^{m} t_{d,i} \qquad (2)$$

where $T_{d,n}$ refers to the delay in activity n, which comprises of m terminal activities. If there is a delay of 1 day in arranging the reinforcement, we can thus predict that the activity will be delayed by 1 day. This however assumes that more labour is not allotted to the activity to ensure faster completion. The construction progress-reporting module continuously updates the progress and subsequently predicts the completion date of each activity on the construction schedule. The splitting up of activities also facilitates the creation of a resource-loaded schedule. Material information is extracted from the BIM model and linked to the corresponding activity. For example, the terminal activity “arrange reinforcement” is linked with the quantity of reinforcement from BIM model. In our study we use the Revit Application Programming Interface (API) to automatically extract these material quantities and link them with the schedule, which is stored in the csv format. However, automatically linking tasks on the schedule to their corresponding elements in the BIM model is not an easy task. For this reason, we used a naming convention for BIM elements and scheduled activities. This was defined as an additional attribute for each member in the BIM model, which could be read by our program to automate the creation of a resource loaded schedule. In this manner, the schedule indicates not just the activities start and end dates, but also the material consumption pattern. The construction progress report along with the resource-loaded schedule forms the basis of planning the material logistics. However, this framework has certain limitations. Firstly, the granularity or level of development of the BIM model, should match the level of detail in the construction schedule. Secondly, the reporting of construction progress, and amount of materials used, would have to be performed frequently and with a high level of accuracy. Although this may be tedious, having accurate daily reports of construction progress and materials used, allows the sub-contractor to better assess their performance, facilitating a lean process. It will help sub-contractors better plan the amount of materials or labour needed, and may contribute to reducing wastes on the construction site.

CONSTRUCTION SITE SPACE-MONITORING MODULE

Storage spaces on a construction site can be categorised as – (1) exterior storage locations that refer to the areas surrounding the building under construction, and (2) interior storage locations within the building under construction. The primary role of a storage space is to house temporary storage facilities for materials and equipment. The material and equipment needs of a site changes as construction progresses and as a result so does the site layout. Temporary facilities, when not needed anymore, are dismantled so that the space can be used by other facilities. A temporary storage facility is a confined region on site, which is used to store a particular type of material or equipment. The amount of space allocated to each facility is defined at the site layout planning stage and depends on the quantity of material that will be stored in it. Each storage space has a maximum capacity above which it cannot accommodate more materials.

Delays in construction might lead to more materials being delivered to the site, than can be accommodated. This can be illustrated by the following example. Consider the activity of installing lighting fixtures on each floor. Each floor contains one hundred lighting fixtures, with twenty fixtures being installed on everyday. As a result each floor can be estimated to take one week to complete. The lighting fixtures are delivered to the site in batches of 240 fixtures, every 2 weeks to ensure a continuous supply of materials. The storage area is provided such that it can accommodate a maximum of 300 fixtures at a particular time. Now assume that 1 week into the activity, installation of light fixtures has to stop for one week because certain electrical lines have to be rewired. In this situation, it is likely that the second batch of light fixtures will arrive on site before the first batch is utilized. As a result the total number of fixtures on site will be 440, and hence cannot be accommodated by the storage facility. In this situation, space must be allocated to temporarily accommodate the excess materials. The materials should not interfere with any on-going activities, nor create a hindrance for storing other materials. It is also favourable to store them somewhere close to the original storage location, in order to minimize the transportation distance. We use the following 3-step methodology to monitor the available storage spaces on the construction site.

Step 1: Assessment of the storage capacity of the existing facility. The quantity of materials being used up can be obtained in the construction progress-reporting module. The quantity is then subtracted from the quantity of materials delivered to the site to obtain the quantity of material currently stored in the facility. This quantity is then subtracted from the maximum capacity of the storage facility to determine the feasibility of storage. If the materials cannot be accommodated in the temporary facility, they have to be assigned to other storage locations on the site. The following two steps deal with this.

Step 2: Assessment of the available exterior site spaces. Using the site layout plan we check the site for availability of storage spaces. In order to store the material delivery a storage space should meet the following two criteria – (1) it should be vacant during the time period for which the materials will be stored in it, and (2) it should contain sufficient space to accommodate the delivery. Every region on site, which satisfies this, is considered as a possible storage location.

Step 3: Assessment of interior storage spaces. In order to utilize the interior building spaces for material storage, it is important to identify the beginning date when any given floor becomes suitable for storing materials. In most building construction projects, this is given by the date of slab completion. Thus, we assign the start date of interior storage on a given floor as the date of slab completion.

The construction site space-monitoring module can hence tell us about the feasibility of material storage during different time intervals in the construction.

MATERIAL DELIVERY COORDINATION

Coordinating material deliveries is another important aspect of construction projects. As illustrated in figure 1, delays in construction activities might indirectly result in overcrowding of the site space. In our study we use two methods of mitigating excess inventory from accumulating on the site- (1) automated construction progress based pull ordering, and (2) supplier coordination module.

AUTOMATED CONSTRUCTION PROGRESS-BASED PULL ORDERING

The resource-loaded schedule tells us the quantity of materials that are consumed each day by construction activities. The rate of consumption, which forms the basis of inventory management, is then computed for each activity. When the quantity of materials in the inventory falls below a certain threshold, the system automatically registers a material order with the supplier. The date on which the automatic order is made depends on the lead-time and rate of consumption of that material. The order quantity depends on several factors such as the amount of storage space on site, the cost of ordering and the contractor’s appetite for risk. The benefit of this system is that materials are automatically ordered when they get depleted. This is done by defining the reorder point, or the level of inventory that triggers a material order. The order quantity and re-order point are taken as inputs by the contractor. Each batch of materials that have been ordered is then given a unique reference number, for easy identification. Thus, the system will automatically create an order for a batch of materials, based on the progress of construction.

Delays in construction however, cause problems in storing materials on site, especially for longer lead-time materials. As explained in the previous section, delays in construction activities lead to excess materials being stored on site. If a material, which was ordered before the delay got reported, arrives on the site, it is likely that the site may not be able to accommodate it. This is because the site space allocated to this material is still occupied by the material for which there is a construction delay. This problem can be addressed in two ways – (1) postponing the delivery of affected materials, and (2) assigning a temporary storage area on or off-site. Postponing the delivery of subsequent materials requires coordination with suppliers, which is facilitated through the supplier coordination module.

SUPPLIER COORDINATION MODULE

Upon receiving a material order, the supplier coordination module is invoked. The main function of this module is to act as a bridge between construction activities on site and production activities at the supplier. A material order goes through various stages before it gets delivered to the site (see Figure 3**)**.

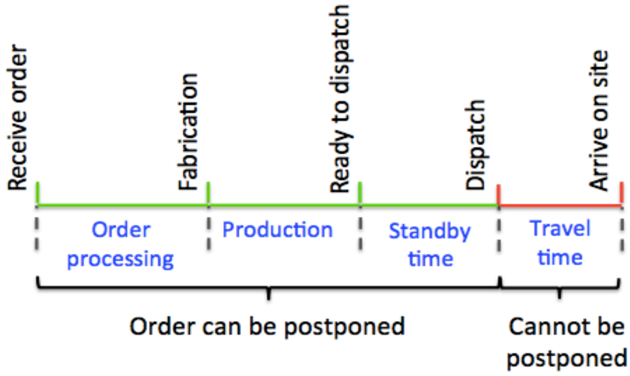

Figure 3: Stages a material order goes through before being delivered to the site

This information is necessary in determining which orders can and cannot be postponed. Postponing orders is vital for construction sites with limited site space, because it prevents crowding on site due to un-coordinated material deliveries. It is quite common for contractors to delay the deliveries of certain materials due to a hold up in construction activities on site. However, once a batch of materials has been dispatched from the supplier's factory or warehouse, it becomes expensive to postpone the order. In such situations, the contractor either arranges for an off-site temporary storage or buffer area, or allows the materials to be delivered to the site. The limitation of our system is that it currently does not consider the presence of such buffer zones. Our system requires the supplier to provide information about material orders on a regular basis in order to determine which orders can be postponed. A user interface will be provided to the supplier for updating the status of a material order. The supplier has to update the date when a material order is – (1) ready to dispatch, and (2) dispatched. Orders that cannot be delayed have to be assigned temporary storage locations either on or off the construction site. The material storage optimization module performs this assignment.

MATERIAL STORAGE OPTIMIZATION

Site layout planning should be carried out on two different levels – (1) tactical planning, which decides the storage location of each material, and (2) operational planning which ensures that the site layout plan is followed on a daily basis. In tactical planning the planned construction schedule is used to determine the material storage requirements and subsequently their storage locations. However, it is very rare for the construction to progress exactly according to schedule and as a result it may not be possible to follow the site layout. It is common practice for the site superintendent to make daily operational decisions regarding material storage that do not adhere to the original layout plan. This becomes problematic on confined construction sites, where site space comes at a premium and must be carefully allocated. In such projects, construction delays often render the site layout plan obsolete and the planning effort goes to waste. In this study we tackle site layout planning on an operational level and optimize material storage decisions in the context of schedule variations. Our system allocates materials in such a way that construction delays have a negligible impact on the site layout plan. This is performed through the following 3 steps:

Step 1: Calculate the amount of space required to accommodate the order. Check if materials arriving on site can be stored in their original storage locations. Yes, then assign them to be stored in original locations. If no, then go to step 2.

Step 2: From the construction site space-monitoring module, determine the possible locations on site where the order can be accommodated.

Step 3: Calculate transportation distance. Finally, the transportation distance is calculated between the new storage locations and the original storage location. This is necessary because the materials would have to eventually be shifted back to their original storage facility. The storage location with minimum transportation distance is assigned to the materials, in order to minimise the transportation effort.

DEMONSTRATIVE EXAMPLE

We tested the BIM-based SCM framework on an illustrative example of a building construction project. The project involves construction of an 8-story steel building with a glass curtain wall façade. Autodesk Revit was used to create the BIM model, which contained the material information of the building, and a site layout plan showing the temporary storage areas for materials was determined (see Figure 4).

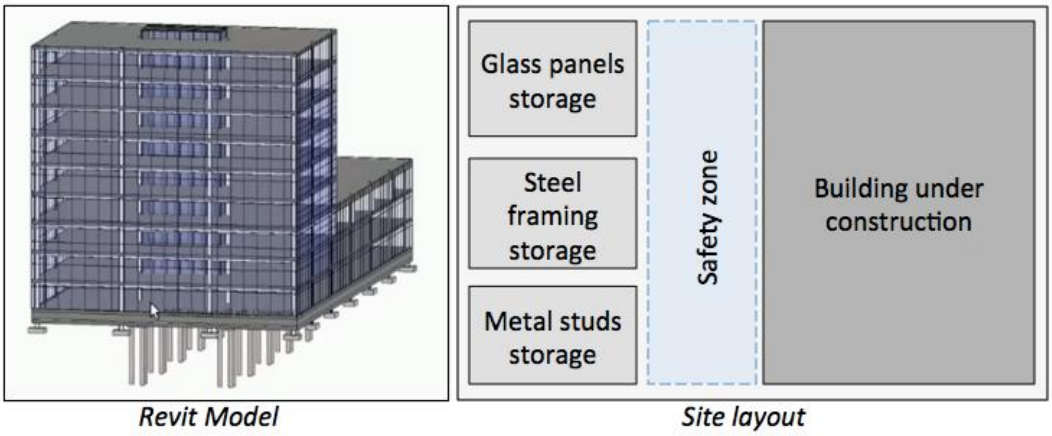

Figure 4: BIM model and site layout plan in the demonstrative example

Our framework is tested on the phase of construction dealing with installation of the glass curtain-wall façade. The major activities in this phase are – (1) installation of curtain wall stud layer, (2) installation of curtain wall framing, and (3) glass windows installations. Curtain-wall studs are first installed on each floor, which are immediately followed by erecting the steel frame. The glass panels are installed once the studs and framing have been completed. Each activity has a cycle time, i.e. the time necessary to complete the activity on one floor and move to the next floor, of 5 working days (1-week). The order quantity, reorder period, installation rate and lead-time of each material are shown in Table 1.

Table 1: Material order information

Activity	Material	Installation rate	Order quantity	Reorder point	Lead-time
Curtain-wall stud layer	Metal studs	200 units/day	800 units	300 units	1 day
Curtain-wall framing	Steel framing	100 units/day	400 units	250 units	2 days
Curtain-wall panels	Glass panels	50 units/day	200 units	175 units	3 days

Each one of these materials would have to be provided with a storage area on-site, which is based upon their maximum inventory level and the available site space. It is determined that the storage areas of the metal studs, steel framing and glass panels can accommodate a maximum of 1000, 500 and 250 units, respectively. Upon reaching the third floor, it is realised that the studs on the second floor were not installed according to specification. As a result, it is ordered that the second floor studs be completely removed and installed correctly, causing a delay of 1-week in the schedule. As a consequence the depending activities would also have to be stalled by 1-week. During this stage of construction the on-site inventory levels for each of the materials is as shown in Table 2.

Table 2: Material order and site inventory status

Material	On-site storage capacity	Current inventory amount	Quantity delivered in next order	Order status	Inventory after next delivery	Additional storage requirement
Metal studs	1000 units	200 units	800 units	Cannot be postponed	1000 units	None
Steel framing	500 units	200 units	400 units	Cannot be postponed	600 units	400 units
Glass panels	250 units	150 units	200 units	Cannot be postponed	350 units	200 units

Our system can foresee the material storage requirements of the project for the following weeks. It can be see that sufficient space to store the steel framing and glass panels would not be available, and as a result it would require material orders to be delayed. At this stage, the supplier coordination module is invoked to check the feasibility of postponing material orders. Since none of the orders could be postponed, the additional batches of materials would have to be accommodated in temporary storage locations on-site. The construction site space-monitoring module is then invoked to determine the feasible storage locations for the additional materials. Since the construction site does not have any additional on-site temporary storage locations, the materials delivered to the site would have to be stored within the built environment of the building. Thus, interior areas within the building can be planned in advance to accommodate the storage of additional materials.

CONCLUSIONS AND FUTURE WORK

Site layout planning has been well studied at a strategic and tactical level however, there is a lack of planning that goes into managing it on an operational level. In this study we presented a system framework for managing the material logistics and site layout for a construction site. The system leverages BIM technology to automate the creation of resource-loaded schedules, which are then used as a basis for planning the site layout and material logistics. Our system enables sub-contractor's to foresee the adverse effects of construction delays on the material logistics of a site and hence plan ahead of time to mitigate them. It also improves coordination between suppliers and contractors, by providing real-time updates about material order information. Using our system, contractors would be able to better gauge their daily usage of resources and would improve their planning and estimation. Future work will focus on extending the proposed framework to account for varying degrees of complexity in materials and site layout management.

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