Applying Object-oriented Analysis and Design to Digital Construction Logistics Planning from a Material Flow Perspective

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Abstract –

Current construction logistics planning in practice is executed as an experience-driven planning and proved as inefficient. Previous outcomes of Building Information Modelling (BIM) provide the fundamental of a digital construction logistics planning. However, an underlying logistics concept and a guidance from the production theory for applying BIM in logistics are missing.

This paper aims to elaborate existing problems in the construction logistics planning and initiate an exploration towards a digital logistics planning with a underlying concept of the on- and off-site material flow. A design methodology of OOA/D (Object-oriented Analysis and Design) is applied to the conceptual design of a digital on- and off-site logistics planning. An object-oriented definition of logistics element with a start from predefined BIM element and a use case about logistics Quantity Take-off (QTO) are explained. The research helps to reflect the material change in the construction logistics more accurately, and to further evoke the rethinking of the production theory in the construction field.

Keywords –
Logistics; Material Flow; BIM; OOA/D

1 Introduction

Logistics is the management of the flow of resource between the point of origin and the point of consumption in order to meet requirements of customers (owner or end-user) or corporations [1]. It is a tough task to achieve an efficient logistics planning in the construction field, because the resource flow of a construction project is broken between off-site and on-site domains. The critical reason is not the geographical separation but the non-conformant resource planning.

With the development of Information and Communication Technology (ICT), the manufacturing industry achieves better logistics planning and control by Product Data Management (PDM) system [2]. The fundamental of PDM is a series of well-structured digital Bill of Materials (BOMs), basically including Engineering BOM (EBOM), Plan BOM (PBOM), Manufacturing BOM (MBOM). The material flow in the manufacturing industry is clearer than it in the construction industry, however, the essence of it is the same. Actually, a construction BOM used at the material purchase stage is a typical EBOM, while a construction Bill of Quantity (BOQ) with schedule is equal to a MBOM. What is missing in construction is the PBOM, which essentially is a data form of the construction logistics planning.

Building Information Modelling (BIM) can be applied to build a digital logistics planning and supports its execution. It is a set of concepts, technics and digital methods to encode information of facilities about 3D design drawings, schedule, material characteristics, costs, and safety specifications etc. BIM model is an object-oriented representation and specified by but not limited to Industry Foundation classes IFC (ISO 16739) [3]. Further, the four-dimensional (4D) BIM (i.e. three dimensions plus time) is capable to improve construction scheduling and site monitoring [4], which can also improve the logistics management in a digital way.

However, an underlying logistics concept and a guidance from the production theory for applying BIM in logistics are missing. Meanwhile, current pattern of logistics planning and control in the construction practice is proved as inefficient, thus it cannot be adopted as the fundamental of the design of a digital logistics planning.

Therefore, this paper will provide an analysis of non-conformant resource planning and adopt the understanding of on- and off-site resource flow to a conceptual design of an efficient digital construction logistics planning. The focus of the digital construction logistics planning which will be introduced in this paper is on the materials, while related equipment or transportation tools are treated as constraint or supplementary conditions of materials.

2 Literature Review

Current construction logistics planning in practice is executed as an experience-driven planning with an as-designed site-layout and a series of periodic (e.g. daily, weekly, monthly) look-ahead schedules, and mainly relies on project QTO (Quantity Take Off), BOM and construction master schedule[5]. Generally, BOM is generated from QTO and is applied for the material purchase with a list of subtotals of each material type, which is a guidance document to calculate the periodic quantity of material supply[6]. Another document BOQ, which is also generated from QTO, is applied to calculate the periodic quantity of material consumption associated with a construction master schedule[7]. The problem is that the quantity of material supply does not match the quantity of material consumption, because of different levels of periodic measurement.

From the consumption perspective, a construction BOQ generally follows a division-component method (e.g. earth work, foundation work, frame shear-wall work) and it is the foundation of most 4D construction logistics planning. For example, Tulke and Hanff (2007) presented a solution for creating schedule based on data from BOQ and the building model[8]. From the supply perspective, a construction BOM applies an enterprise level of periodic measurement (e.g. project duration, sub-project duration) to dovetail with the enterprise accounting. It is possible to introduce in the construction schedule to make a detailed construction plan with material constraints[5]. However, a BOQ from the consumption side applies a periodic measurement based on the division-component project level, which is inconsistent with the supply side.

The difference in periodic measurement between enterprise level and division-component project level directly causes the mismatch of the periodic quantity of material supply and material consumption. It makes construction project management adopt a Just-in-Case strategy towards the material resource. According to the Just-in-Case strategy, the succeed of one or a series of construction tasks is the highest goal and any shortage of on-site inventory should be avoided, which may causes any of following problems, but not limited to the followings:

- Excessive amounts of orders
- Overstock on-site
- Waste of site capacity
- Difficulty in materials and related equipment maintenance
- Difficulty in site monitoring

It is worth noting that, even a good Just-in-Case plan cannot guarantee to avoid failure of a construction task in some situation e.g. major construction change, long term or continuous supply delay.

Therefore, an effective construction logistics planning is not only about the development of an excellent avoidance strategy. To understand and accurately grasp the information of the material flow, to overcome the incompatibility in the periodic measurement, and further to solve the mismatch of the quantity of material supply and consumption are main goals of this paper, which is an initial exploratory of a proactive on- and off-site construction logistics planning.

3 Methodology

There are various approaches to develop a construction logistics plan with as-designed building information and related on-site information. However, to grasp the off-site information properly and try to achieve a proactive digital logistics planning is a challenge, and therefore this paper only focuses on the conceptual design of it. A complete software design or a management mode is beyond the scope of this paper.

This paper adopts a design methodology of OOA/D (Object-oriented Analysis and Design) [9] and it contains two phases, as shown in Figure 1:

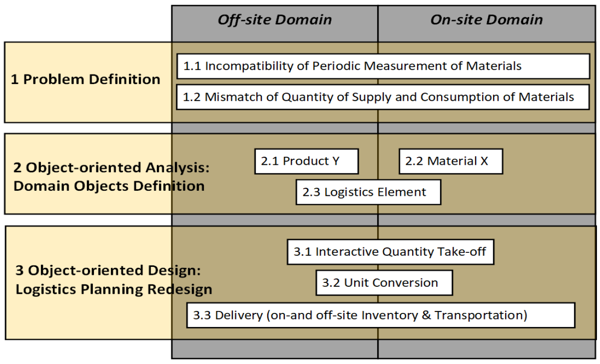

Figure 1. Paper Structure and OOA/D Methodology

1. **Practical Problem Definition**: as discussed previously, is to provide a basic understanding of the weakness of current construction logistics planning and guide the following analysis and design.
2. **Object-oriented Analysis**: with an emphasis on finding and describing the logistics objects or concepts in the problem domain. It is conducted to conduct an analysis of the basic features of the construction material flow from the off-site domain to on-site domain;
3. **Object-oriented Design**: with an emphasis on

defining specific logistics objects and how they collaborate to fulfil the requirements (e.g. attributes and methods). This paper also provides a use case to describe this design by applying Unified Modelling Language (UML).

It is worth noting that, a design and development of a proactive digital logistics planning with both on- and off-site information should be a Iterative process, and this paper provides only the initial efforts.

4 Object-oriented Analysis: On- and Off-site Material Flow

To initiate a construction logistics planning, the first task is to analyse the basic features of the construction material flow. As shown in Figure 2, a certain type of material (e.g. Material **X**) contains three basic status of the physical presences:

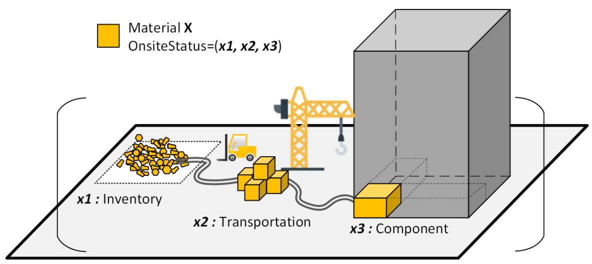

Figure 2. On-site status of the physical presences of Material **X**

- ***x1*** Inventory: on-site stocks of Material X;
- ***x2*** Transportation: Material X in on-site transit;
- ***x3*** Component: Material X placed in one or several construction components.

For an effective construction logistics planning, only considering on-site material flow is incomplete, because the start of a material flow is the off-site production rather than the on-site inventory. Figure 3 illustrates the on- and off-site material flow with a begin of final goods. This paper does not include a complete off-site process because of its scope, however, it can be considered when a construction logistics plan is established.

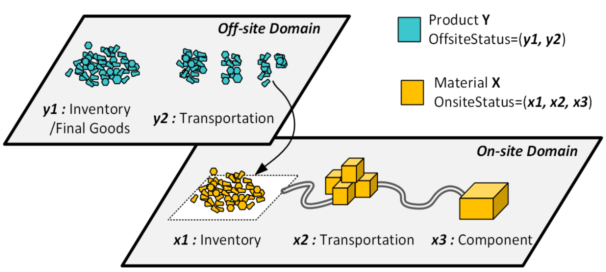

Figure 3. Status of the physical presences of Material **X**

and Product Y along an on-and off-site material flow

As it is shown Figure 3, the off-site form of Material **X** named Product **Y**, in order to distinguish different domains i.e. off-site domain and on-site domain. The off-site data of Material **X** is handled by a supplier. It is more for the supplier to provide required data of Material **X** when it is treated as a kind of product. The physical presences of Product **Y** are:

- ***y1*** Inventory/Final Goods: Product Y ordered by construction project (Final Goods) and produced by a supplier (Inventory);
- ***y2*** Transportation: Product Y in off-site transit.

The difference between Final Goods and Inventory depends on whether the supplier needs to produce this kind of product (Final Goods) or can directly delivery it from the off-site inventory (Inventory). For example, when the production process of a kind of product is error-prone and the supplier usually hold no inventory, it is better for a construction project to treat y1 as Final Goods and pay attention to the status of the off-site production. In this case, an off-site production process look-ahead checking and guarding has been discussed [10].

5 Object-oriented Design: Logistics Element Definition with BIM

According to the nature of the on- and off-site material flow discussed before, it is not appropriate to simply treat a kind of material as a simple attribute of the construction component, which is the traditional way taken by a 4D BIM plan. It is to some degree an oversimplification of the real world and causes the difficulty in applying digital planning in construction logistics.

Actually, the material change of any construction task follows the Law of Conservation of Mass and the essential features of a kind of material does not change along the flow. It provides possibility to apply an OOA/D method to define the Logistics element. It is appropriate to define it from the start of a predefined BIM component (shared building element) which is a long-established practice, as shown in Figure 4:

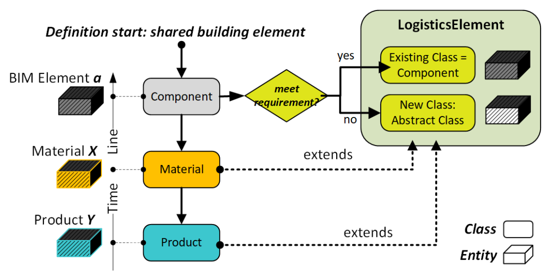

Figure 4. Logistics element definition with BIM

BIM model itself is an object-oriented representation and provides a series of well-designed properties or property sets, which can be applied for LogisticsElement definition. However, it is conditional because of the logistics requirement (see Figure). For example, if the predefined BIM Element ***a*** contains complete property for a logistics plan of Material ***X*** (on-site) and Product ***Y*** (off-site), the definition of them can directly refer to the existing class, otherwise it is required to define a new abstract class to share property.

However, to judge if the predefined BIM element meet the logistics requirement needs to consider both time and quantity parameter and pay attention to different types of materials input:

1. **Simultaneous Materials Input**: includes Single-Material Input (material 1) and Multi-Materials Input (material 1,2..n), as shown in Figure 5. The BIM element of a component contains basic property which can share with materials.

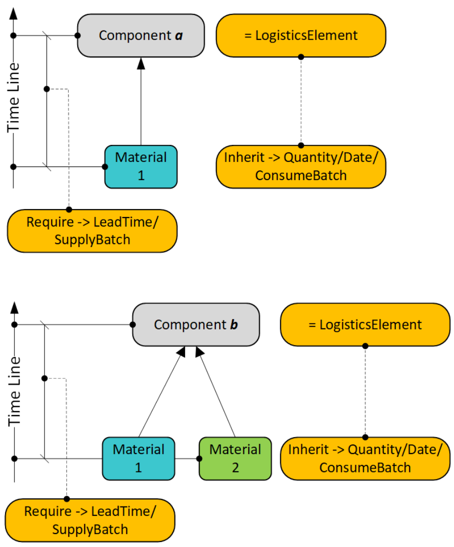

Figure 5. Pattern of the simultaneous materials input

2. **Successive Materials Input**: applies for the situation when the BIM element of a component cannot directly reflect the time and quantity features of every required material. A conversion method is required, for example, to allot quantity of material 1 and material 2 and define time constrains among material 1,2 and component ***c*** (see Figure 6).

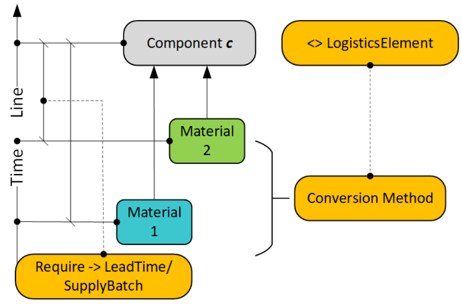

Figure 6. Pattern of the successive materials input

6 Use Case of Logistics Quantity Take-off

- To further understand how to consider the material change as a flow and apply the definition of logistics element to solve logistics planning problems, e.g. mismatch of the quantity of material supply and consumption, a use case of Logistics Quantity Take-off is written (see

Table 1) and explained as following:

Use Case: Logistics Quantity Take-off
Primary Actor: Material Manager, Supplier, Construction Worker, Project Manager
Stakeholders and Interests:

- Material Manager: Wants accurate quantity of construction components and related required materials. Wants sufficient information of supplier's products to support contract and trade.
- Supplier: Wants sufficient information of project required materials to support contract and trade.
- Construction Worker: Wants to finish regular work with no material problem.
- Project Manager: Wants accurate quantity of construction components, related required materials. Wants automatic and fast updates of site transpiration and inventory status.

Table 1. Description of the use case of Logistics Quantity Take-off

Actor Action	**System Responsibility**
1 **Material manager** starts a new **logistics quantity take-off**.	
2 **Material manager** selects **construction components** (known quantity).	3 Records each selected **construction component**, identifies its **material items**

	and calculates material subtotals of quantity with a **material catalog**.
4 **Material Manager** repeats steps 2-3 until indicates done.	5 Logs the completed calculation, presents **material item specification** and generates a classified list of **Quantity of Materials**.
6 **Material Manager** sends **Supplier** related partial list of **Quantity of Materials**, sends an **enquiry** and asks for a **product item specification**.	
7 **Supplier** sends the **product item specification** to **Material Manager**.	8 Handles **product item specification** and converts the **unit** and calculates product subtotals of quantity with a **product catalog**.
	9 Logs the completed conversion and presents a classified list of **Quantity of Products**.
10 **Material Manager** sends **Supplier** related partial list of **Quantity of Products** and an **offer**.	
11 **Supplier** gives an acceptance to the offer and both sides reach a **supply contract**.	12 Handles and records the **supply contract**.
13 **Material Manager** and **Supplier** decide the quantity of **product supply batch** (inventory input) according to the **product catalog**, **price policy**, **material consume batch** (inventory output) and **inventory policy**.	14 Records the **product catalog**, **price policy**, **material consume batch** (inventory output) and **inventory policy**, and calculates **product supply batch**.
	15 Logs the completed calculation and presents **a list of product supply batches**.
16 **Supplier** deliveries **product supply batch** according to the list.	17 Records each delivered **product supply batch** quantity and sends information to the **off-site inventory** systems (update off-site inventory) and the **off-site transportation** systems (update transportation status).
18 **Product supply batch** arrives the construction site and is put into the **on-site inventory**.	19 Records each arrived **product supply batch** quantity and sends information to the **on-site inventory** systems (update inventory)
20 **Construction worker** takes materials from inventory.	21 Records **material consume batch** quantity, and sends information to the **on-site inventory** systems (update inventory) and the **on-site transportation** systems (update transportation status).

** Conceptual classes are in bold*

In this use case, there are three essential tasks which influent logistics status:

3. **QuantityTake-off**: is to work out a model-based Quantity of Materials which supports the division-component project level of periodic measurement;
4. **UnitConversion**: is to get sufficient information from supplier and work out a model-based Quantity of Products, to avoid an excessive Just-in-Case strategy;
5. **Delivery**: is to balance the batch amount of product supply (off-site) and material consumption (on-site) and keep both off-site and on-site inventory safe and economical.

The QuantityTake-off process to generate a Quantity of Material is a model-based process i.e. ConstructionComponent and MaterialItem contain their own quantity information, rather than adding material attributes to a list of QTO (i.e. list-based BOM). As discussed before, the list-based BOM applies an enterprise level of periodic measurement and it is insufficient to a logistics planning. The model-based Quantity of Materials is explained as following:

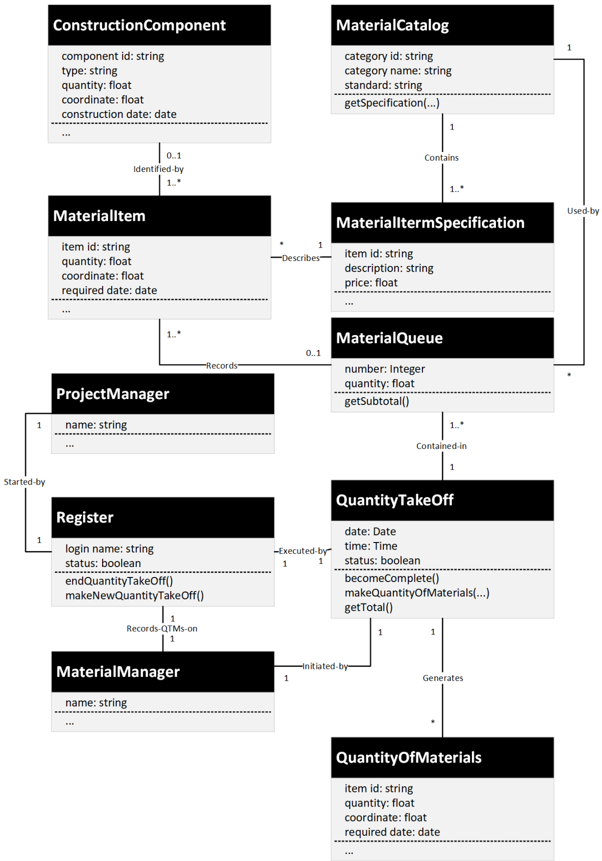

Figure 4. Domain model of QuantityTake-off

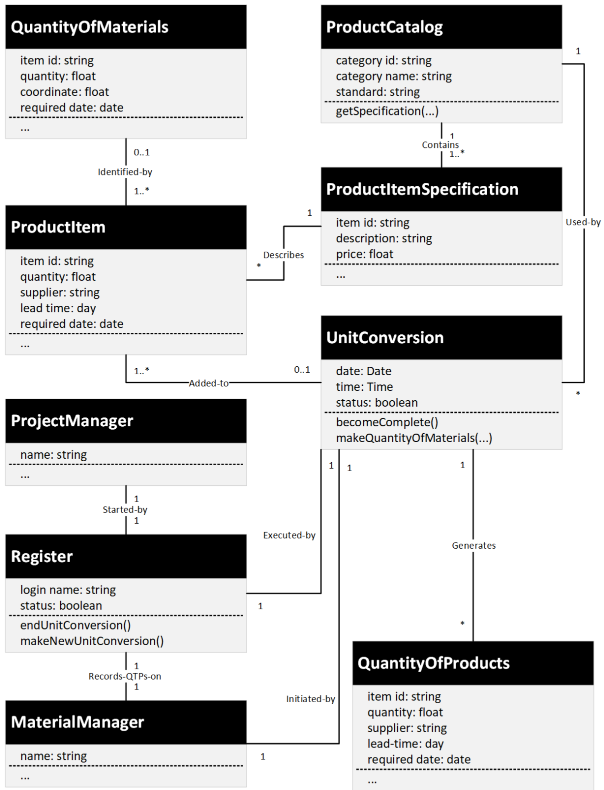

Figure 5. Domain model of UnitConversion

Besides Quantity of Materials, there is another important document: Quantity of Products, which is treated as an essential conjunction of the on- and off-site logistics at the planning stage. This Quantity of Products is a concentrated reflection of the off-site information from both sides. To work out a Quantity of Products, the Quantity of Materials and production specification are needed as the fundamental and a UnitConversion method is applied as following:

After Quantity of Materials and Quantity of Products both worked out, specific MaterialConsumeBatch and ProductSupplyBatch are taken into account. To design an optimized ProductSupplyBatch is not a simple task, because the on and off-site production, transportation and inventory data should be collected and a series of policies should be considered e.g. PricingPolicy and InventoryPolicy, as shown in Figure 6:

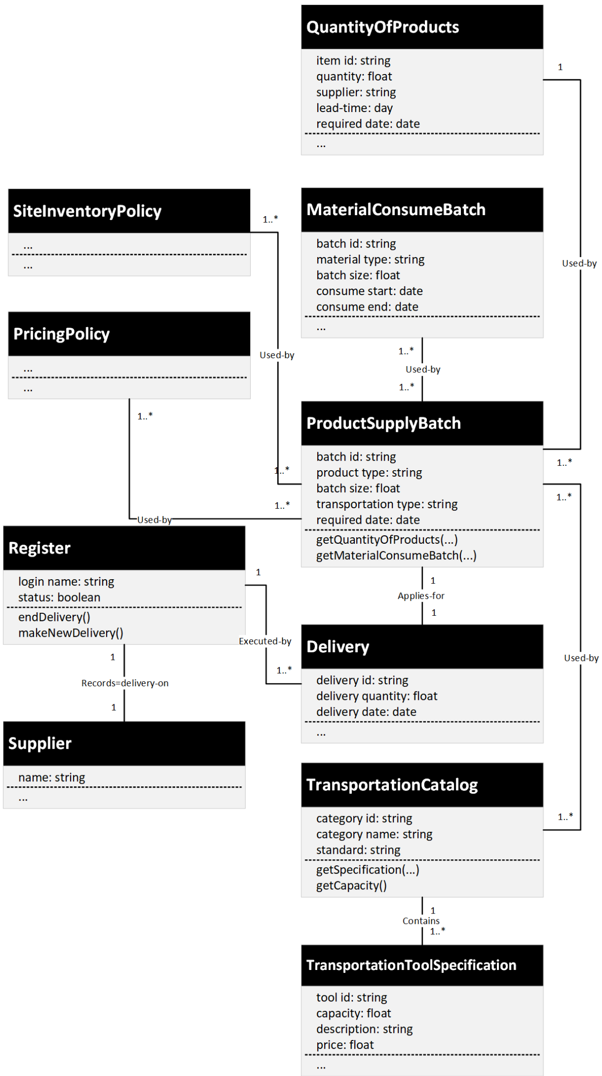

Figure 6. Domain model of Delivery

These three essential tasks of QuantityTake-off, UnitConversion and Delivery in this use case are essential to overcome the incompatibility in the periodic measurement, solve the mismatch of the quantity of material supply and consumption and further to develop more detailed on- and off-site logistics planning.

7 Conclusion

The aim of this paper is to explain existing problems in the construction logistics planning and initiate an exploration towards a digital logistics planning with a underlying concept of the on- and off-site material flow. This paper first introduced the material flow and analyzed the basic status of the physical presences of a certain type of material from the on-site to off-site domains. Then an object-oriented definition of logistics element with a start from predefined BIM element was discussed. Finally, a use case of Logistics Quantity Take-off with three essential tasks of QuantityTake-off, UnitConversion and Deliver was explained.

However, the logistics element definition and use case at this stage are not complete, there are several aspects need to improve, for example, logistics requirements in element definition should be specified and the method of UnitConversion should be designed in detail. Further, a new pattern of the logistics planning and management is not only to reflect and control the material change to make a project succeed, but also to rethink the construction industry itself and its own production theory.

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