Generating Bills of Materials for Daily Work Orders Consisting of Made-to-stock Materials

By

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Abstract

The time spent for generating a daily bill of materials (BOM) varies depending on the type of construction work at hand. Our observation at construction sites showed that generating a daily BOM can be time consuming when the work consists of made-to-stock (MTS) types of materials (e.g., in the range of 12 - 68 minutes per daily BOM). To expedite this process of generating a daily BOM consisting of MTS materials, this research introduces the concept of a smallest workface boundary (SWFB)—a boundary that operates with level of development (LOD) 400 elements to help a foreman quickly generate a daily BOM. We carried out three field experiments to iteratively improve the concept. This involved building a prototype with SWFBs and going through iterations of asking foremen to use the prototype for generating daily BOMs, and if shortcomings are observed, addressing them and applying the improved version of the prototype to the next experiment. The three experiments took place at construction sites in UAE, Sweden, and Peru with nine trades (three trades at each site). With the latest version of the prototype, the average time it takes a foreman to generate a daily BOM is 59 seconds.

Keywords: bill of materials, daily work order, made-to-stock, LOD400, smallest workface boundary.

Introduction

One of the key information items that constitutes a daily work order in construction is the quantity of materials (Oglesby et al. 1989; Mourgues 2008), and the document that contains this information is often referred to as a bill of materials (BOM)—a list of quantified materials required to build a product (Clement et al. 1992; Mourgues 2008). When a BOM can be generated on a daily level in construction, it helps a foreman to have precise control over the site in terms of where the materials should be, in what amount, and by which date. It also allows site people to delay the delivery of materials until the last moment of installation. In addition, if the daily BOM is available, it can help generating refined controls metrics that are derived based on the quantities, such as daily production rate (when the BOM information is tied to manpower information) and percent plan complete (PPC) (when the planned BOM information is compared with the installed BOM information).

Our observation at five construction sites, however, showed that generating a daily BOM can be challenging if the BOM involves made-to-stock (MTS) types of materials—the types of materials that are stocked at a site and further processed at the site through cutting, bending, fabricating, or applying. To solve this problem, we built a prototype that imports level of development (LOD) 400 elements (AIA (2013)) and operates with what we define as a smallest workface boundary (SWFB)—a boundary that encapsulates a set of LOD400 elements in the smallest workable unit for a certain trade.
With the use of LOD400 and SWFB, the prototype first focuses on improving process metric, that is, improving the speed of generating a daily BOM information. This document reports on three experiments carried out with this goal. The experiment took place in UAE, Sweden, and Peru with the support of CCC, Oscar Properties, and Quality Consulting Solutions, respectively. The trades that we experimented with the prototype were ceiling, glass, and mechanical piping in UAE; facade, planter, and protective concrete in Sweden; and masonry, electrical conduit, and water piping in Peru. These trades all had work involving MTS materials.

Motivations for LOD400 and SWFB

Between 2015 and 2016, we visited five construction sites in UAE and Germany, and collected 831 daily work orders for studying daily BOM—an information item that should be a part of a daily work order (Oglesby et al. 1989; Mourgues 2008). The first finding of the study was that generating a daily BOM consisting of MTS materials is more time consuming than generating a daily BOM consisting of ETO materials. Our observation showed that, for MTS materials, the time ranges between 12 minutes and 68 minutes per daily BOM depending on the construction task at hand, and for ETO materials, it takes about a minute per daily BOM. Generating a daily BOM consisting of ETO materials takes less because ETO materials are typically engineered and prefabricated upfront and this drives the contractors to generate a product-specific shop drawing, which often has a BOM available at one corner of the shop drawing. By leveraging this information in ETO materials, it is possible to build a system that retrieves quantity information quickly for generating a daily BOM. On the other hand, for MTS materials, a typical shop drawing is prevalent instead of a product-specific shop drawing. Examples of MTS materials include track and studs, sheetrock, concrete blocks, wood, and paint, which are typically stocked at a construction site and further processed through cutting, bending, fabricating, or applying. In order to generate a daily BOM for MTS materials, one has to go through additional process of manual takeoff based on a typical shop drawing.

The second finding of the study on 831 daily work orders was that finding corresponding 3D elements in BIM for each of the daily work orders can be difficult when 3D elements are modeled at LOD300. Our study on 831 daily work orders (cards) showed that when LOD300 is used, 29% of the cards will have corresponding 3D elements in the BIM, whereas when LOD400 is used, 98% of the cards will have corresponding 3D elements in the BIM. (This problem is illustrated in greater detail in Song et al. (2017).)

The intuition we got from these two findings was that, if we were to create a system for quickly generating a daily BOM for MTS materials, the system should first rely on importing LOD400 elements.

Fig. 1. The SWFB for track and studs we observed at a site is a wall. In the prototype, we took the wall element encasing the track and stud elements and used the wall element as a reference object for generating a SWFB.
Based on the intuition, our prototype v1 was developed to import LOD400 elements and prototype v2 successively added a concept that we define as the smallest workface boundary (SWFB)—the boundary that encapsulates a set of 3D elements in the smallest workable unit for a certain trade. For example, for a drywall framer in a residential project, a SWFB would be the boundary of a wall that encapsulates track and stud elements (Fig. 1). Prototype v2 was designed to automatically generate these SWFBs for track and stud elements. The prototype was then further designed so that a foreman can use the SWFB generated to select multiple LOD400 elements encapsulated in the SWFB with a single gesture and quickly scope the day’s work and produce a daily BOM. The motivation on creating the smallest workface boundary also came from our literature review where the benefit (e.g., reducing work duration and risk) of creating a small batch size is studied (Hopp and Spearman 1996; O’Brien 1998; Morkos 2014).

Research method

Following the problem identification (Song et al. 2017) and generation of prototype v1 and v2, the goal of this research was to iteratively improve and validate the concept of SWFB (introduced in prototype v2) through a series of field experiments.

The iteration involved providing the prototype to foremen, asking them to generate daily BOMs, refining or supplementing the concept of SWFB if shortcomings were found, and applying the improved version of the prototype to the next site. Through the iterations, the process metric we aimed to improve was the speed of generating a daily BOM using the prototype. And whenever possible, we also tested the speed of generating a daily BOM without using the prototype.

Each experiment took place over a period of three weeks, and the first week of the visit was mostly spent on model coordination, modeling LOD400 elements if necessary, testing interoperability, installing an interactive board, and setting up the prototype for foremen’s use. In field experiment 3, this preparation stage took two weeks, mainly because the project did not have LOD400 elements for masonry walls and additional modeling was required.

Field experiment 1

Field experiment 1 was an airport project in UAE. The subcontractors of the project were required to deliver LOD400 elements to the general contractor so LOD400 elements were available for most of the trades. The three trades selected for the experiment were ceiling, glass, and mechanical piping trades as shown in Fig. 2. The BIM authoring tool for the ceiling and glass trade was AutoCAD and for the mechanical piping trade, Revit. In the first week of the experiment, AutoCAD and Revit files were cleaned up for importing to prototype v2. In addition to this, for the ceiling trade, separate programming was done to extract the quantities of ceiling frames because unlike Revit, the 3D elements of AutoCAD typically do not have quantity properties and this was the case in the project (only geometric information was available from AutoCAD). After importing the LOD400 elements, algorithms for generating SWFBs were developed. This process first involved selecting a reference object. For the ceiling trade the reference object(s) were the two rail frames that support the bridging frames as shown in Fig.
These rail frames were engineered to be 3000mm in length and the SWFB was generated based on this length since the ceiling frames were installed in the units of 3000mm as well. For the glass trade, a glass panel was a reference object for generating a SWFB and this boundary encapsulated the connection parts (angle brackets) between the glass panels. For the piping trade, a pipe was a reference object for generating a SWFB and this boundary encapsulated an elbow or tee at two ends of the pipe and the insulation covering the pipe and elbow/tee. After identifying the reference objects, algorithms were developed to create a boundary that encapsulates the reference object and the connection parts around the reference object. The SWFBs generated with the algorithms are shown in Fig. 2.

At the end of the first week all the elements were imported to the prototype, SWFBs were generated, and the prototype was ready for an experiment. Everyday morning the three trades foremen came to the site office and used the prototype to generate a daily BOM using the SWFBs. In a period of two weeks, the three foremen generated 46 daily BOMs (cards) as shown in Fig. 6—the figure shows the time it took a foreman to generate a daily BOM card. One limitation we found in this experiment was that there were cards that took unreasonably long compared to other cards as shown in the figure and these cards were the cards containing pipe and elbow/tee elements but not the insulation elements. The time took longer for these cards because there was a phasing problem. A SWFB contained both piping elements (i.e., pipe, elbow, and tee elements) and insulation elements, but at the site, the piping elements were installed on a certain day first, and after a hydro test, the insulation elements were installed on a later day: a case where the elements within a SWFB falls into two different phases. So the foreman had to go through the process of excluding the insulation elements in order to first generate a daily BOM card containing only the piping elements for a day but this process took several minutes for the foreman. This limitation was addressed in the next version of the prototype by providing a functionality for selecting only certain types of elements within a SWFB.

Field experiment 2 was a residential project in Sweden. This project had only LOD300 elements so the general contractor selected a portion of the roof area under construction for the experiment and selectively further developed LOD300 elements to 400 elements. This extra modeling started
two weeks prior to the site visit and continued until the first week of the site visit. As shown in Fig. 3, the three trades on the roof were the facade, planter, and protective concrete trades. The elements that were additionally modeled were screws, wooden frames, steel profiles, waterproofing membranes, brackets, and protective concrete rebars.

For generating the SWFBs, a reference object was first identified with the foremen as it was done in the previous experiment. For the facade trade, a wall was a reference object; for the planter trade, a planter box was a reference object; and for the protective concrete trade, the protective concrete under the planter box was a reference object. SWFBs were generated based on the reference objects and the SWFBs encapsulated all the connection or substrate elements within the boundaries. In case of the facade trade, one SWFB encapsulated as many as 180 elements including the connection and substrate elements. From this, we can imagine the benefit of using a SWFB because a foreman can deal with one SWFB instead of 180 elements when selecting LOD400 elements for scoping a day’s work.

An interactive board was installed at the site office as shown in Fig. 3 and the foremen used the prototype to generate daily BOM cards in the similar way as the previous experiment except that prototype v3 was used in field experiment 2. This project also had a trade that had to deal with two phases within a SWFB—the facade trade. In constructing the facade, the workers installed the waterproofing membrane and steel profiles first on a certain day and after ten days, they installed the wooden finishes on top of the steel profiles. During the experiment, the foreman of the facade trade used the phasing functionality newly built in prototype v3, and the phasing problem observed in the previous experiment was not observed in this experiment as shown in Fig. 6.
Field experiment 3

Field experiment 3 was a residential project in Peru. The three trades selected for the experiment were the masonry, electrical conduit, and water piping trades as shown in Fig. 4. In this project, the electrical conduit and water piping trades had LOD400 elements but the masonry trade did not have LOD400 elements. For the masonry trade, a wall remained as a single element in Revit without granular elements (e.g., blocks, connections, and reinforcements), so in the first two weeks of the experiment, additional details were modeled to develop the masonry model to LOD400. The elements newly modeled were concrete blocks, mortar, grouting, and reinforcing bars.

In this experiment, the reference object for generating a SWFB was a wall for all trades even for the electrical conduit and water piping trades. In field experiment 1, the reference object for the piping trade was a pipe and not a wall because the concept of a wall did not exist where the pipes were installed. All the pipes in field experiment 1 were hanging from the ceiling and not contained in a wall, so it made sense to generate a SWFB in reference to each pipe for the airport project. But in field experiment 3, the construction was in the interior phase of a residential project and all the pipes were to be built inside of walls. And given that the installation of the pipes was done in the units of walls to release each unit of wall to the masonry trade, it made sense to generate a SWFB in reference to a wall as shown in Fig. 4.

Another finding worth sharing in this field experiment is the setting of an interactive board at the site. In the previous field experiments, an interactive board was located at a site office. In field experiment 1, the site office was about 5-minute drive from the airport under construction and in field experiment 2, the site office was in an office building next to the construction site. Although this location is close enough for foremen to visit the interactive board daily, in field experiment 3, we learned that an ideal location to install the board is inside of the building under construction as shown in Fig. 5. This location has advantages because it provides better accessibility to the foremen on any time of the day and the foremen can conveniently visit the room without checking or walking out of the building under construction.

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**Fig. 4. SWFBs (yellow boundaries) generated in field experiment 3. The shape of the SWFBs in all trades was determined by the wall object. The shape of the SWFBs in the electrical conduit and water piping trades was determined by the wall object during the interior phase of the construction, because the electrical and plumbing rough-ins were constructed and released in the units of walls so the masonry walls can be built next.**

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Conclusion

For addressing the problems identified with daily BOM consisting of MTS materials, we developed a prototype that imports LOD400 elements. This, however, had limitations: while scoping a day's work, a user of the prototype had to deal with a sheer number of elements and the small sizes of connection elements such as screws or brackets. To overcome this problem, the concept of a SWFB was introduced to prototype v2. We tested prototype v2 in field experiment 1 and Fig. 6 shows the time it took to generate a daily BOM card. In Fig. 6, each bar represents a daily BOM card and the vertical length of the bar represents the time spent to generate a card. In field experiment 1, 7 cards out of 46 cards had a phasing problem where taking additional steps for excluding elements that fall into different phases within a SWFB was necessary and unreasonably long. After field experiment 1, a functionality was added to prototype v3 to help a user quickly differentiate the elements that fall into different phases within a SWFB. We then tested prototype v3 in field experiment 2 and 3, and the average time to generate a daily BOM with prototype v3 was 59 seconds, which is an improvement from 12 - 68 minutes per daily BOM when using other information resources available at the sites instead of the prototype.
Next steps

In the context of the plan-do-check-act (PDCA) cycle, what we have researched so far fits into the stage of the planning—we have used the prototype for generating daily BOMs in the planning stage. For the upcoming research, we plan to take the daily BOM generated in the planning stage and operate it through the remaining stages of the PDCA cycle. For instance, during the Do stage, the quantities in the daily BOM planned can be used for delivering materials on time, and during the Check stage, the daily BOM completed can be generated as well. And during the Act stage, the metrics that are enabled by going through the PDCA cycle, such as percent plan complete (PPC) (derived by comparing the daily BOM planned and the daily BOM completed) can be generated. The PPC generated in this way would be LOD400-based PPC, which can be analyzed on a daily level as well. We look forward to addressing the remaining stages of the PDCA cycle in future research.

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References


