**Proposal number:** 2018-01  
**Proposal title:** Operating LOD400-based daily BOM through the PDCA cycle  
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**Total funds requested:**  
**Project URL for continuation proposals:** [https://cife.stanford.edu/Seed2017_BillsOfMaterials](https://cife.stanford.edu/Seed2017_BillsOfMaterials)  
**Project objectives addressed by proposal:** Buildable  
**Expected time horizon:** 1 year  
**Type of innovation:** Incremental

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**Abstract (up to 150 words)**  
**The problem:** A study on 831 daily work orders collected from five construction sites showed that generating a daily bill of materials (BOM) would be time consuming for 68% of the work orders consisting of made-to-stock (MTS) materials (e.g., 12-68 minutes/daily BOM). This also prevents foremen from operating a daily BOM through the plan-do-check-act (PDCA) cycle.

**The proposed solution:** Our field experiments, based on our 2017 seed proposal, used level of development 400 (LOD400) and a smallest workface boundary (SWFB) to expedite the generation of daily BOMs (materials planning stage in the context of the PDCA cycle). In continuation to this, we propose operating the generated daily BOMs through the remaining stages of the PDCA cycle.

**The proposed research approach:** We plan to carry out two field experiments, operate LOD400-based daily BOMs through the PDCA cycle, and generate metrics enabled by going through the whole cycle, such as LOD400-based percent plan complete (PPC) or daily material quantities anticipated correctly.
Introduction

A bill of materials (BOM) is a list of quantified materials required to build a product. In construction, when a BOM is included in a work order, it helps construction workers understand the scope of work quantitatively, establish a baseline for comparison, and maintain focus on the value added by the work. Once this baseline is established with a BOM, it can be used throughout the cycle of plan-do-check-act (PDCA) for comparing work planned v. work done, materials ordered v. materials spent, materials cost planned v. materials cost incurred, among many other indicators. Generating a BOM is helpful in many ways, but the challenge we have found is when a foreman wants to generate a BOM on a daily level for a certain type of material. In case studies done in 2016 at five construction sites, we found that operating a daily BOM through the PDCA cycle is particularly challenging for made-to-stock (MTS) types of materials (Song et al. 2017). In last year’s seed proposal, we focused on the materials planning stage of the PDCA cycle and used level of development 400 (LOD400) and a concept we define as a smallest workface boundary (SWFB) to help foremen quickly generate a daily BOM consisting of MTS materials. As an extension of this research, we propose to operate a daily BOM generated with LOD400 and SWFB through the remaining stages of the PDCA cycle and to generate metrics enabled by going through the cycle, such as LOD400-based percent plan complete (PPC) or daily material quantities anticipated correctly. We hope to contribute to the topics of “feedback loops” and “closing the gap between assumed and actual conditions” addressed in this year’s call for seed proposal.

Observed problem

If the necessary information can be formulated quickly enough, a foreman should be able to start a day with a list of materials planned to be built on that day (Plan), head out to the field and fabricate and install the materials (Do), check the quantities planned v. quantities completed of the day (Check), and react to deviance from the plan if necessary (Act). A study on 831 daily work orders collected in 2016 from five construction sites showed that, given the project engineering resources typically available on site, going through this cycle could be achieved for 29% of the daily work orders only, which were typically related to engineered-to-order (ETO) materials, because these materials often have a ready-made, product-specific shop drawing with BOM information. Furthermore, we found that by leveraging this ETO information, we can create a system that rapidly generates a BOM that can be operated through the PDCA cycle on a daily basis (green loop in Fig. 1). However, for the remaining daily work orders which were related to made-to-stock (MTS) materials (68% of the daily work orders), this was
challenging because a foreman needs extra time and effort to generate a BOM based on a typical shop drawing (rather than a ready-made, product-specific shop drawing). For instance, taking off quantities with a typical shop drawing for an acoustical ceiling (MTS material) requires time and effort (red loop in Fig. 1).

Points of departure

To overcome this observed problem for MTS materials, we proposed a prototype at the CIFE Technical Advisory Committee (TAC) meeting in April of 2017. The intuition for the prototype came from our field observation that BIM at LOD400 would have the required elements for generating a daily BOM consisting of MTS materials (Song et al. 2017) and from our literature review that a small batch size is beneficial in production (Hopp and Spearman 1996; O’Brien 1998; Morkos 2014). Building on the intuitions, our first version of the prototype was developed to import LOD400 elements and the second version successively added the concept we define as the smallest workface boundary (SWFB)—a 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. 2). The prototype was then made so that a foreman can use the SWFB to select multiple LOD400 elements encapsulated in the boundary in a single gesture and rapidly scope the day’s work and produce a daily BOM.

At the TAC meeting in April of 2017, we also proposed conducting field experiments with this second version of the prototype and were given the opportunity to proceed with the proposal. Based on the proposed work, we visited two construction sites—one in Abu Dhabi, the other in Stockholm—and tested the prototype with three trades at each site. We selected trades that involve MTS materials since, as mentioned in the Observed Problem section, generating a daily BOM for this type of material is challenging. The three trades at the Abu Dhabi site were ceiling, glass, and on-site-cut pipe trades, and the three trades at the Stockholm site were facade, planter box, and protective concrete trades. For each trade, we then created SWFBs encapsulating LOD400 elements as shown in Fig. 3.
Fig. 3 SWFBs generated for six trades in field experiment 1 and 2. A SWFB encapsulates LOD400 elements in the smallest workable unit for a trade.

In field experiment 1, three tradesmen generated 46 daily BOM cards in a span of three weeks. The time to generate a BOM card ranged from 7 seconds to 27 minutes and 45 seconds, with an average of 2 minutes and 40 seconds. A notable finding from this experiment was 7 daily BOM cards that took substantially longer than the remaining cards (called out in Fig. 4). The difference between these 7 cards and the rest of the cards (for which it took less than a minute to generate a daily BOM) was that, for the 7 cards, the tradesman had to segregate a set of elements that were to be installed on a different day from the rest of the elements within the same SWFB. In other words, the process of generating a card took longer when the 3D elements in a SWFB were to be installed in multiple phases. Fig. 5 shows a case where this phasing problem is present. In this SWFB, the pipes, fittings, and valves were to be installed on day 4 (phase 1), and the insulation covering these elements were to be installed on day 10 (phase 2). The 7 cards took longer to generate a daily BOM because when a tradesman used a SWFB, the SWFB fetched all the elements within it without a perception of phasing, i.e., the SWFB was not useful for targeting a specific phase.
Based on the observed shortcoming, the next version (version 3) of the prototype was made to allow a tradesman to either select all elements within a SWFB or select a certain type of elements (e.g., all insulation elements). This improved version of the prototype with the concept of phasing was used in field experiment 2 in Stockholm. The three trades were facade, planter box, and protective concrete, all of which were executed on the roof, and all the trades had two phases within a SWFB. For instance, for the facade trade, the first phase was to install waterproofing membrane, steel profiles, and screws, and the second phase was to install wooden panels and screws. In field experiment 2, three tradesmen generated 33 daily BOMs cards in a span of three weeks and the time to generating a BOM card ranged from 23 seconds to 2 minutes and 8 seconds with an average of 43 seconds. In comparison to field experiment 1, the average time had improved from 2 minutes and 40 seconds to 43 seconds.

During the field experiments, we also asked tradespeople to generate a daily BOM card without using the prototype but using preexisting information at the site, such as shop drawings. The time
to generate a card ranged from 12 minutes and 9 seconds to 68 minutes and 20 seconds—far longer than the 43 seconds achieved when the prototype with the concept of phasing (version 3) was used.

**Research methods and work plan**

The two field experiments illustrated above showed that a tradesman can generate a daily BOM in about a minute with prototype version 3. Generating daily BOMs in this way establishes the materials quantities to be installed on certain days and connects the daily work tasks to the BIM. In the context of the PDCA cycle, this falls into the materials planning stage (P of the PDCA cycle) and establishes a baseline at LOD400 for the remaining stages of the PDCA cycle.

The materials quantities planned can be used to control the materials flowing into and within the site in the Do stage of the PDCA cycle. Then the actual materials quantities installed can be recorded against the quantities planned in the Check stage of the PDCA cycle. And when these stages are completed, we should be able to generate metrics to be reflected on in the Act stage of the PDCA cycle. The metrics that can be generated include the following:

Percent Plan Complete (PPC)
Comparison of
  material quantities on site
  material quantities installed
  material quantities wasted

Note that the PPC here is not based on a task or its control quantity, but on quantities of every elements at LOD400 in a daily BOM. This BOM-based PPC can show how a full list of daily material quantities are anticipated correctly. Also similarly the tracking of the “material quantities installed” above does not only include a control quantity, but all the material quantities needed for fabrication and installation as represented in the daily BOM.

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*Fig. 6 Operating LOD400-based daily BOM through the remaining stages of the PDCA cycle. The red area is the proposed scope of research.*
We propose conducting two field experiments using LOD400-based daily BOMs to generate the above metrics enabled by going through the PDCA cycle (Fig. 6). In the process of generating the metrics, we plan to measure the time required for the process. We also plan to compare this time with the time needed to generate the same metrics with the best available method at the site without using the prototype.

Expected results

The two experiments we propose will be carried out with the goal of improving the speed of generating metrics enabled by going through the PDCA cycle, such as the BOM-based PPC. In the previous two experiments completed, the foremen spent around a minute for generating a daily BOM with prototype version 3 (materials planning stage in the context of the PDCA cycle). In going through the remaining stages of the PDCA cycle, we anticipate a foreman spending similar time (a minute or two) for updating material quantities installed against the daily BOM planned. Once the planned and installed quantities are provided by the foreman, BOM-based PPC will be made available by computations in the prototype. If the time for updating a daily BOM and generating BOM-based PPC is off our expectation, we will improve the method and implement the revised method in the next experiment. Through the iterative experiments, we will formalize the method for operating LOD400-based daily BOM through the PDCA cycle and generating metrics enabled by going through the cycle.

Industry involvement

We thank CIFE members CCC and Oscar Properties for the access to their projects that have helped us validate version 2 and 3 of the prototype for the Planning stage of the PDCA cycle. For validating the next versions of the prototype for the remaining stages of the PDCA cycle, we are looking for two (or more) industry collaborators who are interested in operating LOD400-based daily work orders and BOMs through the PDCA cycle and generate metrics enabled by this operation, such as BOM-based PPC. The necessary field equipment for the experiment include an interactive board (e.g., Nureva Span Board, SMART Board, Epson BrightLink Display product) and LOD400 elements consisting of MTS materials. In addition to these, the ideal site would have IoT devices, such as beacons and gates, for tracking incoming materials so the incoming materials can be compared with the planned and installed materials available from our prototype.

Research milestones and risks

We expect the duration of a field experiment to be three weeks, but the time frame may be extended depending on the complexity and scope of a project, and also depending on whether materials tracking devices are available. We hope to conduct the first experiment in the Summer Quarter 2017-18, the second experiment in the Autumn Quarter 2018-19 and deliver an article covering the methods for operating LOD-400 based BOMs through the PDCA cycle to the industry collaborators no later than the Spring Quarter 2018-19. The risk we foresee are the
difficulty of finding a project that has LOD400 elements consisting of MTS materials and equipped with an interactive board.

**Next steps**

In the coming months, version 4 of the prototype will be programmed with the capabilities of generating material quantities planned and material quantities completed, and a comparison between planned and completed quantities. At the same time, we will reach out to industry collaborators in order to find a site for the field experiment. When a site for an experiment is agreed upon, we will need to understand LOD400 modeling protocols of the project and test data imports and exports, which, based on our experience, takes about two weeks.

**References**


