A Conceptual Model for Transformation of Bill of Materials from Offsite Manufacturing to Onsite Construction in Industrialized House-building

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Abstract –

Lending inspiration from the manufacturing industry, industrialized house-builders have adopted some of its characteristics such as high standardization of configurable products and manufacturing processes. Standardization of product and information flow within industrialized house-building has shown to beneficially increase offsite manufacturing efficiency. They have however not been able to transfer the increase in efficiency to onsite construction, leading to it being one of the key issues resulting in delays. For offsite manufacturing, previous research has suggested Bill of Material (BOM) as a structure to define information for in manufacturing phases. However, due to the variation in workflow between offsite manufacturing and onsite construction, the structure of a BOM for offsite manufacturing cannot be reused in onsite construction, ultimately resulting in increased data redundancy and recreation.

A conceptual model of a BOM for onsite construction has been developed inspired by Bill of Materials (BOM), Work Breakdown Structure (WBS), Location Breakdown Structure (LBS), Standard Operating Procedure (SOP) and Work Instructions (WI). The conceptual model utilizes space structure LBS to link spaces with SOPs. Furthermore, it also utilizes WBS to link SOPs with WIs.

The BOM for onsite construction is generated by a transformation from offsite manufacturing P-BOM. Streamlining the information flow and transformation between manufacturing and construction phases open the possibility to develop IT-solutions for industrialized house-builders. By developing existing IT-systems to reduce data redundancy, the fragmentation between offsite manufacturing and construction sites could be utilized by reusing existing data. The conceptual model supports multiple information views and allows for information filtering determined by the performed work and project.

Keywords –

Bill of Material; Industrialized House-building; Data Redundancy; Work Breakdown Structure; Location Breakdown Structure; Work Instructions; Information filtering; Offsite Manufacturing; Onsite Construction

1 Introduction

Industrialized house-building (IHB) has been considered as one of possible solutions to achieve the desired increase in effectiveness and efficiency of the construction sector [1]. It has therefore been a major research area in Sweden, where the Swedish construction sector has been a driving force in achieving a substantial development of industrial house-building. IHB has been characterized by high standardization in platforms for basic house types, configurations as well as offsite manufacturing [2]. It has shown several benefits within the construction sector, including assurance of product quality, higher productivity, improved control over manufacturing processes and even improved storage management within onsite construction [3]. IHB has led to an increase in the amount of information produced, handled and gathered around a project [4]. Usage and distribution of information within offsite manufacturing have drastically improved in recent years through a highly integrated offsite engineering, design and manufacturing process [2,3].

IHB could potentially improve the efficiency of onsite logistics, material handling, progress tracking and other onsite activities [3]. To achieve that, its management system must be well integrated with the already existing offsite manufacturing systems. This is however far from reality, where onsite construction is wasting resources searching, sharing or recreating of data, indicating a clear information flow detachment between prefabrication, assembly and construction site [5].

The degree of redefinition is based on the needed level of flexibility to achieve the desired customer value from the product [6]. Therefore, it is important for the information structure to be flexible according to company needs and clients demands.

Inspired by the manufacturing industry, some companies in the industrialized construction sector have adopted information structures relying on the Bill of Materials (BOM). BOM has the potential to describe the breakdown of a product for IT systems, with the intention of organizing information in a form that makes it usable to visualize multiple information views as well as different phases of a product's life cycle [7,8]. For this, BOM structures need to be integrated with the existing manufacturing systems [3].

The purpose of this study is two-folded. First, explore how BOM could be extended to onsite construction. Secondly, analyze how the extended BOM for onsite construction could reduce data redundancy as well as fragmentation between offsite manufacturing and onsite construction.

2 Research Approach

The study uses Hevner's design science (DS) approach [9], focusing on data collection from five case studies consisting of unstructured interviews, observations and supplemented by a literature review. DS is utilized to research and explore models for onsite BOM, by combining unstructured interviews and observations from case studies to identify practices and structures of construction sites.

Three companies have been observed in the study, two IHB companies (A and B) and one traditional construction company (C). In total these make up five study product cases, two with company A, one with company B and two with company C. A and B have been chosen due to them being the leading IHB companies in Sweden and have during the latter years focused on their processes and information flows, thus represented the leading edge of digitalization of the industry. C is one of the five biggest contractors in Sweden and focuses on construction site digitalization.

The literature review has been an iterative process; each phase of the research has yielded concepts that have been further reviewed and incorporated into the paper, which also has led to further unstructured interviews and discussions. The literature review started out with basic concepts such as the status of Information structures, BOM, Building information modelling (BIM) and Information filtering.

3 Theory

3.1 Information structure & Bill of Materials

A major limitation in current Building Information modelling (BIM) practices is the prevailing activity-based focus of the construction industry, rather than information-centric [10]. Information structures, attributes as well as multiple information views are important for an IT-system to be able to support a variety of construction processes under the life cycle of a building [11]. A way to handle this is through standardization in the form of BOM. Creation of a common information structure and a basis for information flow provides the opportunity for IHB to integrate their products into IT-systems and therefore simplify communication not only within the company itself but also with other companies [7]. BOM can be used to describe the structural breakdown of a product and its relationship with sub-assembly, parts and materials. The BOM has the intention of organizing information so that it can be used in IT-systems under multiple different phases of its life cycle and for a variety of cases by using different information views optimized for each specific task [7,12,13].

When it comes to BOMs in construction, more specifically in IHB, research has exemplified definitions created for design and offsite production phases, there is however little published research on onsite construction within the context of IHB.

Within design and offsite manufacturing, research focuses mainly on Engineering BOM (E-BOM), Manufacturing BOM (M-BOM) and Process BOM (P-BOM) as well as their transformations, see Figure 1. Transformation between these BOM types occurs by modifying the information structure hierarchy, adding or even deleting data from the parent BOM [8]. E-BOM often works as the essential source of information for all other types of BOMs, meaning that all other forms of BOMs are subtypes of an E-BOM [8]. Therefore, it is important to keep E-BOM as the foundation of BOM structure when a transformation occurs.

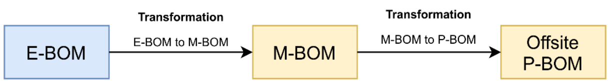

Figure 1. BOM Transformation [7].

Research defines E-BOM as a BOM utilized by designers with the intention to represent the product structure from an engineering viewpoint and is often produced by CAD/BIM systems [14]. M-BOM represents the manufacturing assembly sequence of a product. Its structure is perceived as a series of hierarchical groups and is generated from an E-BOM transformation, in which additional information of manufacturing sequence is added to the structure [14]. P-BOM is utilized in offsite manufacturing and is generated from an M-BOM transformation with inclusion of detailed process information for assembly of modules and its components [8].

3.2 Location Breakdown Structure

Location Breakdown Structure (LBS), see Figure 2, is a hierarchical structure of spaces that can be used within a project [15,16]. LBS is intended to decompose spaces into smaller units, where each descending level has higher detail of space definition, resulting in a more usable and manageable LBS. Space is a geometrical volume which contains information describing a specific portion of the construction site as well as its relation to other spaces. Different detail levels can be used depending on the needs of each task. Detail planning and finishing related tasks is often preferred to be conducted at the highest level of detail [17]. The highest level in the LBS hierarchy usually represents the construction site of the project, and the lowest level often is represented by apartments. However, it is also possible to have each individual room in the apartment at the lowest level.

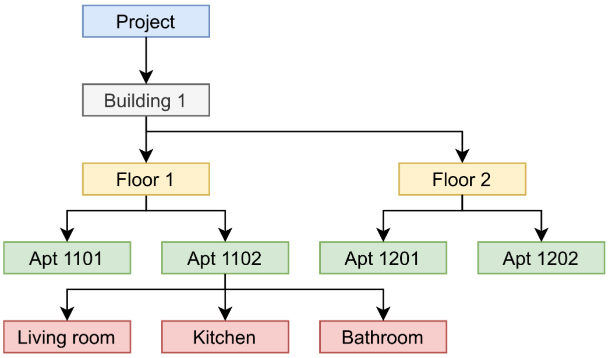

Figure 2. LBS example for a construction project.

3.3 Work Breakdown Structure

Work Breakdown Structure (WBS), see Figure 3, is a project breakdown from the perspective of construction tasks, where the completion of the project is related to the tasks being done [18,19]. WBS is intended to decompose the tasks into smaller tasks that are more manageable by creating a hierarchical structure of tasks [20,21]. Each descending level in the WBS hierarchy represents the subdivision of tasks and an increase in detail of task definition. Usually, the highest level represents the entire project and the lowest level being work packages. It is at work package level that tasks can be assigned to individuals, teams or even contractors [20,22]. WBS must be used with an appropriate level of task detail, as unneeded decomposing will end up requiring additional management efforts and higher cost [20]. Using WBS can improve process management, process definition, scheduling, risk analysis, cost estimation and project organization [21,23].

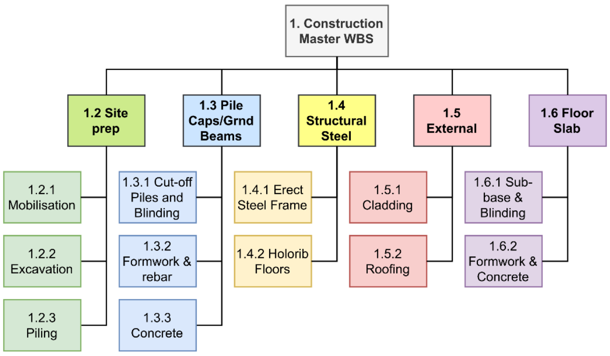

Figure 3. WBS example for a construction project [24].

3.4 Standard Operating Procedure & Work Instruction in construction

Standard Operating Procedure (SOP) is a documented manual of a company's established practices [25]. According to Nakagawa, a well-documented SOP utilizing companies' experience is essential to reach increased construction quality and consistency as well as reduction of scheduling waste, environmental impacts and safety risks [26]. To achieve its goals, a SOP needs to contain information about construction methods, assembly sequence, activity duration, safety instructions and preparatory work [25,26].

Work instruction (WI) is a documented manual of a company's construction methods [27,28]. Traditionally, it is created as text documents containing a list of instructional tasks to guide the assembly process of a building project, it can include shop drawings, 3D models, animations and pictures [29]. A WI includes sequenced instructional description of tasks, safety information as well as a list of resources such as tools and materials [28,29]. To avoid assembly process errors, delays and damaging the credibility of WIs, it is of utmost importance to ensure that WIs are updated in a quick manner [29,30].

4 Conceptual Model Development

The current information structure according to studied cases of offsite P-BOM cannot be reused for onsite construction, with the main reason being the variation in workflow. The industrialized offsite manufacturing and assembly process is done in a factory single assembly line. Components and parts are being assembled while the semi-finished modules are being moved from one workstation to another. Meaning that the factory defines specific workstations in which specific tasks and resources are being used. This enables optimization of tasks and resource management within the factory as well as minimizing the resource usage. Due to spaces being the non-movable components in onsite construction. Instead, it is now the workers and resources that are being moved. While the construction is ongoing, unlike assembly line production, new spaces are becoming available, leading to a more complex and dynamic relation between spaces that needs to be taken into consideration.

This paper proposes the creation of a new BOM for onsite construction, called **onsite BOM**. Onsite BOM aims to improve data sharing by streamlining the information flow process and reducing data redundancy. For that, an onsite BOM is defined, its transformation as well as its dependencies.

4.1 Transformation of BOM

Generally, all forms of BOM transformation are derived from either E-BOM or M-BOM [8]. However, due to the existence of reusable information within offsite manufacturing, and to achieve the aim of reducing data redundancy as well as information recreation, the concept is instead based around a transformation of offsite P-BOM to onsite BOM, see Figure 4. This transformation gives access to information that before was unavailable to the construction site and had to be recreated or modified. From E-BOM, it gets access to information about module types, properties, location of modules as well as components within modules. It even gets access to space data from E-BOM, information used to identify room types, room properties while simultaneously identifying module relations as well as space requirements and limitations. Sequence of module assembly for onsite construction is available from the M-BOM and can be used to identify delivery order of modules, assembly order of modules as well as delivery date estimation to construction site.

Offsite leftover tasks are leftover tasks allocated to onsite construction from offsite manufacturing and the information is available to access from P-BOM to identify additional work instructions required for project completion. Reuse of its data can result in data redundancy reduction as currently this data is manually recreated by site managers as well as skilled workers.

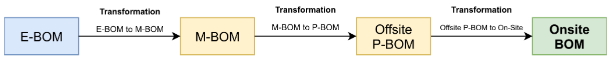

Figure 4. Concept of BOM Transformation from offsite P-BOM to onsite BOM.

4.2 Location Breakdown Structure

To manage and utilize generated spaces within onsite construction a concept of LBS for IHB has been developed from the case study, in which variations of space types and their relation are identified according to needs of IHB.

- The highest level in the LBS hierarchy embodies the whole space that the construction site will occupy, called Product or Project.
- The first descending level in LBS is Buildings, this hierarchy embodies the separate buildings within the product to create a distinction between the building volumes as well as maintain information independently between them.
- The second descending level in LBS is Levels, in which spaces are hierarchically organized with a higher level of detail according to their floor level in the building.
- The third descending level creates a distinction between apartments and stairwells, in which all apartments and stairwells are identified.
- For apartments, the fourth descending level in the hierarchy maintains information about the room, including its room type.
- The lowest descending level in LBS is Modules, it defines the bounding space of modules manufactured offsite and is derived from either Room or Stairwell.

This structure of LBS gives an identified module relation with other modules by identifying which modules create which rooms or stairwell, see Figure 5.

In the concept, Modules have been put as the most detailed level of the space, while they arguably could have been placed under Buildings or even under Levels. Information on Modules are often only required in early stages of onsite construction with exception to offsite leftover tasks, while Levels and Apartments are used from the beginning until completion of construction. Therefore, having the highest level of detail results in it not being required as often when performing construction tasks and can therefore be more often filtered from the information view.

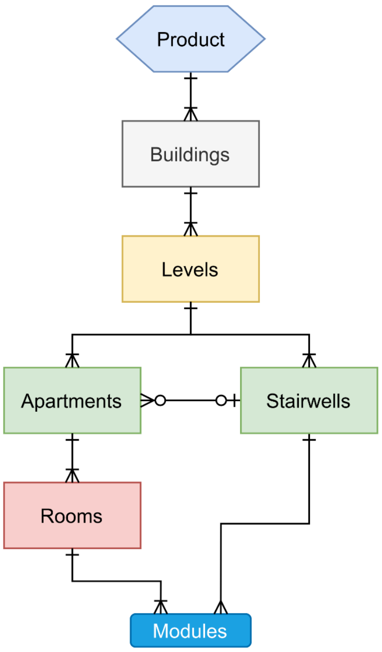

Figure 5. Concept of LBS for IHB projects.

4.3 Relations of BOM for onsite construction

The concept, Figure 6, utilizes the structure of LBS to link spaces with SOPs to create a relation between construction tasks and associated spaces. Each work instruction within a SOP contains information of what spaces it needs to be performed on, with what resources as well as what its space restrictions and requirements are. To put in context, see Figure 6, a SOP is performed for replacement of a window due to a leftover task. It includes two WIs, one for removal of the window and one for its installation, due to it being a leftover task, the SOP is linked to the Module, the highest level of detail, and therefore accessing the available information about the module from offsite P-BOM, including type, dimensions and other specifications of the window.

The concept has spaces as the sole carriers of construction status to establish a communication hub with all other SOPs. The links between WI, SOP as well as LBS ensures a consistent information interoperability between them under all levels of detail. Information interoperability is essential to dynamically modify the sequence of WI and SOPs to adjust according to construction sites continuously changing demands. It is

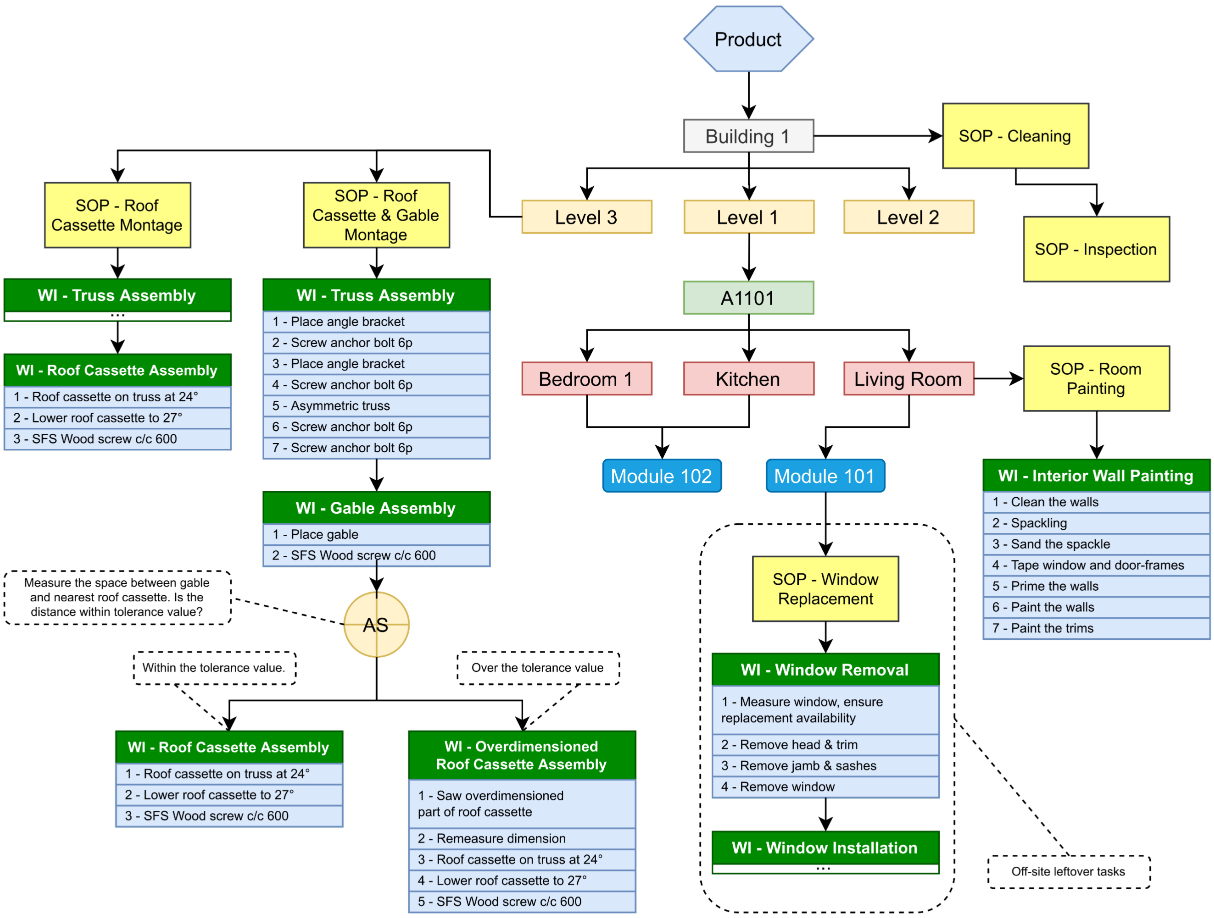

Figure 6. Concept of onsite BOM for IHB projects linking LBS with SOPs, WIs, AS and instructions.

also essential, when looking for an information structure that supports information filtering, as in showing the right amount and type of information to the right target group in information views. Information needs to be interoperable in the information structure for it to be synchronized and filtered to the correct target group. The breakdown structure of information makes filtration possible as it specifies all the existing relations under all levels of detail for the system, therefore showing the ones needed as well as the ones that can be filtered out. The existing types of relation in the concept are: Space – Space, Space – SOP, SOP – WI, SOP – Alternative sequence, Alternative sequence – WI, WI – WI and WI - Instructions.

Alternative sequences (AS), see Figure 6, are alternate WI arrangements within a SOP that can be triggered for foreseeable changes or issues that can be required to conduct a SOP correctly. The study shows that AS changes the sequence of WI within a specific SOP. A SOP has therefore accessibility to information available within its WI sequence and AS. AS consists of a ruleset describing its intentions, multiple alternative WIs and a description of said WIs. It reduces the managerial demands for when modifications are necessary, for example due to weather or construction tolerance related issues that occur commonly. In addition to that, it decreases data redundancy by reducing the need for modification of construction sequence as well as recreation of WI specific for special cases.

The conceptual BOM is built to ensure that SOPs can be assigned to any space independent of its level of detail. This is done by ensuring that available and required information within spaces stay consistent independent of spaces level of detail. Inspired by the hierarchical structure of the decomposed task structure of WBS, a hierarchical structure of SOP, WI and instructions have been developed and later been integrated with LBS. To put in context, see Figure 6, a SOP was developed for roof cassette montage, it has been broken down into two WIs and further into seven and three instructions, respectively.

A SOP is linked to a space either directly or through one of the SOPs it is linked to in a sequence. In cases where a previous SOP exists, that SOP must be fully completed, or as an exception for it to be moved to the next SOP in the sequence. According to theories, a SOP has the requirements of containing a title, description of its usage and step-by-step instructions, known by WIs.

To secure quality of work and safe work procedures, foremen and site managers can use lists of predefined WIs. According to theories and interviews a WIs for onsite construction needs to include an instructional description of itself, safety notes, list of tools, machinery, components, materials, instruction durations, space requirements, space restrictions, number of required skilled workers as well as their work qualifications.

In addition, the study has shown the need to link SOPs to spaces for identification of task locations. AS is required to quickly be able to adjust to constant construction demands and changes. SOPs correlation with WI is designed with intention to reduce data redundancy as well as the need for recreation of said data as the occurring data sharing between SOP and WI.

The concept may achieve this by ensuring that no data redundancy exists between SOP and WI, and that data only exists in a single place with a single owner. Additionally, it aims to ensure that a SOP gets access to all data within its WIs and therefore be able to further generate additional information such as a dynamic list of resources to a changing construction site such as when delays or shortages occur.

5 Discussion & Conclusion

The adopted characteristics of the manufacturing industry, in which most of its engineering and manufacturing is done offsite, this study highlights some major issues with IHB. The existing need of conducting a certain amount of work at the construction site has been a bottleneck, the non-structured information flow has led to data redundancy and fragmentation between offsite manufacturing and onsite construction, further increasing the issues. By usage of BOM structure, this concept aims to improve data integration, reduce fragmentation by streamlining the information flow. Additionally, identifying information types and possible transformation sources of the information to the construction site could ensure that data redundancy can be minimized.

Based on observations, onsite construction in IHB mostly utilizes shop drawings, Excel sheets and to some extent even cloud storage with none of them promoting data integration. Resulting in data redundancy, information is recreated into separate documentation with no bi-directional connections.

A real-time information view opens the possibility of optimizing the construction site and its sequence, by filtering the information and showing only the necessary information to the user. Concept hierarchical structure of level of details opens the possibility to filter information based on a variety of parameters, such as locations, number of skilled workers, their qualifications, etc. Making it possible to generate information views, as an example, a view for a painter, in which the painter gets access to information displaying SOPs and WIs associated with tasks they are qualified to and is ready to be performed.

Leftover tasks were a common occurrence that worsened the situation for construction sites by increasing the demand for communication between onsite and offsite. Non-standardization of the tasks and information availability has resulted in site manager's not being able to optimize the workflow or assign teams for conducting these tasks, ordering of replacement components and parts has been a demanding process. Therefore, we believe that transformation of BOM to onsite BOM would facilitate the work of the site manager, since the factory can potentially utilize the transformation to allocate leftover tasks with SOPs and resources, thus reducing data redundancy and data fragmentation between offsite and onsite. Furthermore, transparency of SOP and WI communication has the possibility of reducing the risk of construction errors.

Onsite BOM has the potential to simplify the process of maintaining and updating SOPs as well as WIs within a construction. This is done through standardizing of information flow and information requirements between offsite manufacturing and onsite construction as well as the whole company in general. A combination of the information structures of WBS, LBS, SOPs and WIs has shown the potential to manage the information flow by BOM for onsite production.

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