Construction Parts in Building Construction Projects: Definition and Case Study

By

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CIFE Working Paper #WP142
August 2017

STANFORD UNIVERSITY
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Abstract

In contrast to the manufacturing industry, value added per work hour has not increased over the last 50 years in the Architecture, Engineering, and Construction (AEC) industry. One of the major causes is the limited shared understanding of input products among construction project participants related to value-adding processes. To improve the shared understanding of input products, a new term “construction part” is proposed. The definition of a construction part (i.e., a fundamental unit of building input product) was formulated as a common denominator for construction management (and fabrication/construction???) information about input products. To focus on the value added by construction crews and to allow cross-project comparisons, this definition is shaped to be consistent, value-focused, and quantifiable. This paper discusses the consistency and quantifiability of the definition and decomposition method for construction parts as illustrated through a case study. Future work will concentrate on validating the applications and benefits of establishing the construction part concept as proposed in this paper through building ontologies and case studies on part-related metrics.

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Database subject headings: construction parts, construction productivity, value-adding, building information sharing
Introduction

The Architecture, Engineering, and Construction (AEC) industry has seen a 20% decline in value added per work hour (i.e., productivity) in the United States from 1964 to 2012, while that in the manufacturing industry increased by 200% during the same period (Teicholz 2013). Some manufacturing sectors, such as the aerospace industry, share common features with building projects in the AEC industry — for instance, both have physical end products that are very complex and require high levels of physical labor, time, and money. In spite of this similarity, the manufacturing industry employs more formalized knowledge than the AEC industry regarding input products, which are raw materials or semi-processed products used in the production process to create the final output product (Groover 2010; Lal et al. 2005).

In the manufacturing industry, two main contributions of the shared fundamental unit (i.e., part) of input products as a common denominator of formalizing the knowledge make it especially valuable to enhancing the production processes. First, the unit enables multiple stakeholders to evaluate project characteristics (e.g., complexity) and performances (e.g., safety, progress) related to value-adding processes in a simple, flexible, and structured manner. For example, both Boeing and Airbus know that their 747 and A380 jumbo jets have about 6 million parts, which are the fundamental unit of input products (CNN 2013; Airbus 2014). Using this information, they often estimate the complexity of their production processes.

Second, the fundamental unit also supports clear delivery of production plans related to value-adding processes in a systematic way. This, in turn, enables production teams to (1) follow the instructions without additional information; (2) intensify feedback loops resulting from
collaboration among multiple disciplines; and (3) learn from previous projects in a structured manner. For example, by using the geometric and non-geometric information about input products formalized at multiple levels of detail (e.g., modules, assemblies, parts), the production planners are able to generate clear assembly instructions (Erdős et al. 2014). Another example is Design for Manufacturing and Assembly (DFMA), which is a method of designing a product to be manufactured and assembled efficiently without losing the original product functionality (Molloy et al. 1998). Projects with DFMA have around 50% fewer parts, 50% shorter cycle time, 40% less material and labor cost, and are 60% more reliable (Ashley 1995). Without shared understanding of the fundamental unit of input products, the production teams cannot obtain sufficient benefits from DFMA because the success of DFMA requires deep analysis of each individual part and the collaboration of a multidisciplinary team.

While the manufacturing industry captures information about input products formalized from the shared fundamental unit and uses it to support production management, the AEC industry lacks such information. Thus, the AEC industry often has difficulty simply quantifying metrics (e.g., complexity, modularity) related to value-adding processes, which correlate to the number of the fundamental units of input products.

This lack of knowledge also prevents clear delivery of detailed designs and construction plans, adversely impacting building construction projects. For example, a survey showed that a 21st century construction project has 796 Requests for Information (RFIs), which require an average of 6,368 hours plus $859,680 for processing (Hughes et al. 2013). In general, more than 50% of construction RFIs require simple clarifications due to insufficient information (Tilley 1997).
Moreover, the incapability of clear delivery limits the ability to intensify the feedback loops and learning experiences from previous projects in a structured manner. Thus, before actual implementation of value-adding processes, construction planners cannot conduct deep analyses to make decisions about how to install input products and which input products to prefabricate or preassemble in a structured and collaborative manner. As a result, project planning is usually performed to the level of a weekly look-ahead schedule (AACE 2010), and quantity takeoff methodologies often rely on approximation and rough vendor quotes. Construction labor productivity is positively correlated with the implementation of management programs, such as front-end planning and materials management (Shan et al. 2016). Therefore, if project teams had access to more detailed information about building input products formalized from a shared understanding of the fundamental unit, better project planning would be possible, which would help improve productivity. However, the lack of detailed information and the limited attention to the management of building input products leads to inadequate planning and unnecessary costs, which cause construction projects to falter.

**Research questions and scope**

As the first step to formally collect information about building input products, the research team was required to define their fundamental unit adapted to the unique characteristics of the AEC industry. To do so, two research questions arose:

1. How can the AEC industry define a fundamental unit for building input products that is consistently applicable and quantifiable for value-adding actions at work face?

2. Given the definition, how can industry professionals formally decompose the commission-ready building product into the fundamental units?
Before developing a generally applicable definition of the fundamental unit for the AEC industry, the research team first limited the scope to building construction projects to minimize the effect of topographic conditions on projects, which require increased attention to project-dependent factors. In addition, the team focused on values considered at work face, where construction crews create the final products (Womack and Jones 2010). Work face is also important because it is where workspace conflicts and congestion of value-adding processes, which affect productivity and safety, are often observed (Akinci et al. 2002; Mallasi 2006; Pregenzer et al. 1999; Thabet and Beliveau 1997).

The research team formulated four criteria to evaluate the adequateness of the definition of the fundamental unit of input products for building construction projects: irreducibility, representativeness of values at work face, consistency, and quantifiability.

*Irreducibility*: For a fundamental unit to be self-explanatory of value-adding processes, it needs to be irreducible. This criterion is essential as value should be focused on the most fundamental unit where value cannot be further decomposed but only aggregated, like prime numbers in prime factorization.

*Representativeness of values at work face*: To enhance construction planning processes, Lean focuses on the value-adding steps, which are often conducted at work face, and construction crews create the final products at work face (Womack and Jones 2010; Pregenzer et al. 1999). In addition, improvements in productivity and safety need to resolve congestions and workspace conflicts of value-adding processes, which are often observed at work face (Akinci et al. 2002; Thabet and Beliveau 1997). Thus, the definition should represent values at work face.
**Consistency**: A consistent definition is important because AEC professionals should have a common understanding of the fundamental unit of input products and share their attributes (e.g., information about input products and their installation plans) across disciplines. In addition, some advanced planning methods from the manufacturing industry, such as DFMA, take place between concept design and final design and require several iterations (Meeker & Rousmaniere, 1996). Thus, the definition needs to be consistently applicable from the start to the finish of a project, and across multiple AEC disciplines.

**Quantifiability**: In this paper, the quantifiability of definition means the ability of definition to support computation of various metrics, which are expressed by some formula using the number of units as a variable. Thus, using the definition, the AEC professionals should be able to quantitatively compare the evaluation criteria among multiple projects or specific conditions of the project (e.g., specific services, installation completion status) because the total numbers of the units in a project or under a project’s specific conditions correlate with evaluation results of metrics.

**Research methods**

To answer the first research question, the research team developed an operational definition of the fundamental unit for building input products. Because the operational definition is a procedure agreed upon for translation of a concept into measurement of some kind, the development of the definition also required formulating the classification schemes of the fundamental unit and their associated decomposition methods, which are necessary for the second question (Deming 2000). The team then conducted case studies to evaluate how adequately the fundamental unit of input products is defined for building construction projects by using the four criteria.
**Points of departure**

To formulate an operational definition of the fundamental unit for building input products, the research team reviewed the definition of a part in the manufacturing industry. Because the definition had to be tailored to building construction projects, current AEC approaches for storing and illustrating product information are discussed, namely, Bill of Materials (BOM), building product classification systems, and Building Information Modeling (BIM). These approaches are used to organize input products physically or virtually on the system or trade level, and they are considered key tools for the current AEC industry to manage its building information.

*Definition of a part in the manufacturing industry*

Because a part is often used for the fundamental unit of input products in the manufacturing industry, the definitions of a part were investigated to specialize them for the building construction projects. Webster's Dictionary defines "part" as "one of the often indefinite or unequal subdivisions into which something is or is regarded as divided and which together constitute the whole." A part is also defined in the manufacturing industry as a solid entity that has specific geometries and material properties (An et al. 1995).

These definitions support quantification of input products, which could be used as metrics of projects. However, they cannot provide clear guidance on the decomposition of products considering value-adding processes and are not consistently applicable for continuous products used in the building construction projects. Thus, they should be tailored to represent decomposition guidance for building input products.
Bill of materials (BOM)

Bill of Material (BOM) is a complete listing of all pieces, parts, assemblies, and any other items that are required to build and ship a final product to a customer (Popov et. al 1998). BOM transforms a final product from functional-based schedules in design to an as-built list in production. The manufacturing industry uses BOM throughout the product life cycle, managing the physical components as well as the data related to these components. BOM serve as the basis for inventory control, cost estimating, change management, and many other tasks.

In the AEC industry, BOM are typically distributed across all subcontractors, and its information and corresponding knowledge are rarely integrated. Even if we integrate all BOM in the process, the information within BOM cannot represent values at work face, as it is impossible to gain location information of the materials listed and, more importantly, whether this material is one that will be installed to the final building product at the work face or as a component of an assembly that will be installed at the work face. The existing BOM system cannot satisfy our criteria that it be representative of values added at work face.

Building product classification systems

UniFormat and MasterFormat are the two most widely used classification systems for describing construction input information in the AEC industry. UniFormat is based on functional units, which are typically at the system or assembly level-of-detail (CSI 2011). It is a top-down approach to breaking down the building to support system-level pricing and performance evaluation. UniFormat provides a good basic structure to break down a building into systems, but does not go down to the detailed product level, comparable to the manufacturing industry. Thus, one
UniFormat item often includes many input products, such as air terminals, supply and return ducts, control units, and the connectors and hangers to support the ducts. Generally, workers from multiple trades will install these components separately in multiple actions, yet they belong to one UniFormat item. Since UniFormat does not capture detailed information for each component that requires a distinct effort to install, it is difficult to use Uniformat to accurately analyze and quantify construction effort at work face. Thus, UniFormat fails in fulfilling the criteria of being consistently quantifiable across all trades and a representation of values at work face.

MasterFormat is organized by work result (CSI 2011). It holds information about the requirements and activities of different types of construction work. MasterFormat is a detailed list of construction work and work results, but it can be hard to identify information regarding building input products based on work results. Examples of MasterFormat entries include project progress, such as bids, meetings, and proposal forms, and requirements, such as regulatory requirements, product requirements, and execution and closeout requirements. As a result, a single building input product can fall into multiple MasterFormat entries because it requires several construction activities. For example, a steel beam will need scheduling, lifting, and anchoring. Hence, the information related to construction activities on this particular input product is still separated in MasterFormat. As a result, MasterFormat fails to represent values at work face in a coherent manner.

**Building Information Model (BIM)**

BIM supports a more collaborative virtual project environment, and BIM tools allow the AEC industry to keep digital records of building elements and building information. The AEC industry
used a specification named Level of Development (LoD) to define the contents and reliability of information contained in a BIM element over the project duration. A higher LoD (from 100 to 500) indicates more detailed, developed, and reliable information (graphic and non-graphic) for BIM elements (BIMForum, 2013).

However, BIM rarely contains all the physical entities that combine to form the building product, especially all related information for the fundamental units of entities. Although as-built BIM is gaining gravity as more effort and resources are put into building BIM, detailed BIM is still uncommon in the industry. Also, LoD is based on UniFormat; in other words, information is stored based on the classification system as defined in UniFormat. Therefore, on a system level, they rarely contain construction details associated with each element, exhibiting the same problems as with UniFormat by not relating BIM elements to values added at work face.

**Operational definition of fundamental units for building input products**

This section demonstrates an operational definition of the fundamental unit for input products specialized for building construction projects. To formulate an operational definition, the research team followed six steps: (1) identify the characteristic of interest; (2) select the measuring instrument; (3) describe the test method; (4) state the decision criteria; (5) document the operational definition; and (6) test the operational definition (Graham and Cleary 2000).

This section first introduces the definition, relating it to the first and second steps. The decomposition method for building products into the fundamental units is then presented to describe the test method in detail. In addition, to state the decision criteria, the end of this section
describes the rationales for identifying whether or not the specific entity of building products considered is the fundamental unit defined. To discuss the test results of the definition, the subsequent section describes one example case among multiple case studies conducted.

**Defining a fundamental unit for building input products**

The definition of fundamental units for input products should be generic across all building projects. For a smooth transition from the manufacturing industry to the AEC industry, this definition of a construction part is developed to be irreducible, consistent, value-focused, and quantifiable.

To this end, the research team first identified the characteristic of interest—namely, the fundamental unit that represents values at the work face for our industry. Instead of selecting a physical measuring instrument, the team took into account installation actions to quantify value adding processes at work face. Although multiple trades and projects have different building products, the installation actions cover a large range of construction activities (e.g., pouring concrete, erecting steel components, painting), emphasizing the LEAN concept of value (Womack and Jones 2010; Pregenzer et al. 1999).

Using installation actions, the team tailored the definition of parts in the manufacturing industry for building projects (An et al. 1995). The team calls the fundamental unit of building input products the *construction part*, which is defined as follows:

A construction part is any entity that requires an act of installation at work face to become a component in the final building product.
In comparison, the manufacturing industry describes a manufacturing system with inputs, transformation process, and outputs. In such a system, inputs go through transformation processes to create the outputs; such inputs can be materials, energy, or labor whereas the outputs can be final products, information, or waste. Therefore, the input products, or parts for manufacturing industry, include all inputs except labor, energy, technology, and facility (Lal et al. 2005; Anil 2008). Compared to the definition of input in the manufacturing industry, this operational definition of a part in the construction field conveys the same idea: Construction parts go through transformation processes to become the final building product. Although this definition of a part is more specific than the inputs in the manufacturing industry, it is inspired by manufacturing concepts such as the LEAN concept of value and the fine level of detail in BOM. Instead of the system or assembly level of classification in UniFormat and MasterFormat, this definition of a part intends to cover “all pieces, parts, assemblies and any other items that are required” to build a building project (Popov et al. 1998).

**Decomposition of building products into construction parts**

To explain the quantifiability aspect when coming up with the definition of a construction part, the part is further distinguished into two categories: discrete and non-discrete. This is due to the complexity of construction materials that come in two common forms, either solid or liquid. The objective of differentiating construction parts into these two categories is to provide consistent logic when counting construction parts. For example, given these two categories, it is possible to count one steel column as one part and one fresh concrete pour as one part. This enables the project team to develop a project’s count for the total construction parts without worrying about varied
units of measure. This approach also allows clear communication among different stakeholders as they are talking in the same “language.”

**Discrete and non-discrete construction parts**

The discrete and non-discrete part categories are designed to be mutually exclusive and collectively exhaustive. Any part, as defined for the AEC industry, can be categorized as either a discrete part or a non-discrete part. A non-discrete part is recognized by the following features:

- Construction parts with a viscous flow in the initial state, such as a liquid or gel. Typical examples are paint, spray, asphalt, or glue. Viscous construction parts do not need to be uniform; fresh concrete, cement, and mortar are also non-discrete construction parts in this case.

- Construction parts with small particles, such as gravel, cobble, or sand. Such construction parts normally have a large quantity and are installed by a certain volume. These particles do not add value to the building individually; they only perform its function when joined together. Most filler materials are non-discrete construction parts.

- Construction parts whose exact amount of use cannot be estimated before final installation; examples include tapes, nails (installed via nail gun), or strip seals. In each installation cycle, these construction parts are used to fulfill their purpose (connecting or sealing). Construction workers typically determine the actual amount of use based on their own judgment.

Non-discrete construction parts have one or more of the above features. Any part that cannot be recognized as a non-discrete part is categorized as a discrete part. Discrete construction parts always have clear boundaries, such as columns, beams, and windows.
Counting method for discrete and non-discrete construction parts

For discrete construction parts, one part is counted when it is installed in the building as one piece. In other words, if bricks are installed piece by piece, each brick is counted as one discrete part. Nonetheless, based on the definition, if a prefabricated mechanical, electrical, and plumbing (MEP) rack is assembled off site and installed on site as one, even though the MEP rack contains many pieces, the rack is counted as one discrete part. Similarly, on-site pre-assemblies such as a gypsum board with a wood frame are counted as one part if they are assembled on site and lifted into position as one piece. The size of a discrete part and its weight, volume, or length are all part attributes and are not used for counting. Furthermore, the process where one discrete part is installed in the building can be recognized as one working cycle.

To maintain consistent counting logic for construction parts, non-discrete construction parts have similar counting methods: One non-discrete part is all the material the construction crew installed or applied to the building in one complete working cycle. The actual amount used in each cycle, typically measured by volume, area, or linear length, is a part attribute and is not used for counting. AEC professionals can determine the measurement of different working cycles for non-discrete construction parts as follows:

- For fresh concrete, cement, or mortar, each cycle is from the start of pouring to the setting of that pour. For a concrete floor slab, there can be several pours; as each pour is a part, each part may have a different surface area/volume.
- For gravel, cobblestone, sand, or soil, the cycle is similar to that of concrete, with compacting or tamping as the working cycle’s end trigger.
• For paint or spray, the cycle is often determined by section. Each time the crew paints one section, the paint used in that section is one part. The section can be one wall or part of the wall. The actual amount of paint used becomes a part attribute. Instead of treating each time the workers apply paint to wall as one cycle, the section approach includes some preparation work in each working cycle, such as wrapping the section edge before painting. The wrapped section edges are not construction parts because they are temporary and not a component of the final building.

• For tape, glue, and strip seals, the number of cycles is determined by the installation procedure. For example, the glue used to close the joint between two edges is one part, and the strip seal used to seal a pipe is one part.

In general, it takes one working cycle to install one part, whether a discrete part or a non-discrete part. Discrete construction parts have clear boundaries whereas non-discrete construction parts are bound by the amount of material installed in one working cycle (Table 1). Discrete construction parts often help determine the working cycles for non-discrete construction parts, mostly when they are interacting with each other and physically connected, such as welding and gluing. In these scenarios, the number of joints between discrete construction parts at the work face reflects the number of working cycles (i.e., the number of non-discrete construction parts). Using this working cycle approach, discrete construction parts and non-discrete construction parts share similar counting logic for the construction parts. Therefore, construction parts are quantifiable, the idea behind and logic used in counting construction parts are consistent, and the total number of construction parts in a project can thus be reasonably assessed.

Table 1: Discrete and Non-Discrete Construction parts Summary
<table>
<thead>
<tr>
<th>Category &amp; Features</th>
<th>Example</th>
<th>One Working Cycle</th>
<th>One Part</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Discrete Construction parts</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clear Boundary</td>
<td>Beam, Brick</td>
<td>Install a Part</td>
<td>A beam or a brick</td>
</tr>
<tr>
<td><strong>Non-Discrete Construction parts</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid or Gel</td>
<td>Fresh Concrete, Paint</td>
<td>Each Pour or Section</td>
<td>All the fresh concrete used in one pour, or all the insulation tape used to properly insulated a pipe</td>
</tr>
<tr>
<td>Small Particles</td>
<td>Gravel, Sand</td>
<td>Each Compaction</td>
<td></td>
</tr>
<tr>
<td>Unknown Amount of Use</td>
<td>Insulation Tape, Sealer Band</td>
<td>When Desired Quality is Reached (i.e., a pipe is properly insulated)</td>
<td></td>
</tr>
</tbody>
</table>

**What is a part and what is not a part**

According to the definition of a construction part, construction materials need to meet two key conditions to be construction parts: (1) the material must belong to the final building product and (2) it requires installation by construction crews. Therefore, construction parts can be anything from big components such as foundations, walls, and roofs to small materials like nails, paint, and studs.

However, several things on construction sites do not match this definition of a part. These include waste or spare products, temporary construction materials (e.g., falsework, soldier beams, or lagging), supporting elements like concrete formwork or scaffolding, and equipment or tools. Construction materials left in the building, whether intentionally or accidentally, that should or
could be removed are not construction parts. They are not necessary for the final building product and fall into the categories of waste or supporting elements.

A construction part should be recognized as the way it is when it is installed in the building at its designated location; its sub-assemblies are sub-construction parts or the part’s construction parts. For example, an I-section steel column has web and flange, which are not individual construction parts. Similarly, when a rebar cage is preassembled on site and placed into position, the rebar cage is one part; its bars are not individual construction parts, but rather only sub-construction parts of the cage. These distinctions are important for counting all the construction parts that require installation. Detailed quantification rules are discussed later.

The logic behind these rules is to make sure construction parts really focus on the direct customer value — namely, the final building. By excluding waste, temporary or supporting elements, and sub-assemblies, the definition of a part targets only the necessary physical materials that the building consists of and nothing more. This approach helps the construction team understand how much effort and how many resources are spent directly on the final building and how many on the rest. Such knowledge supports construction teams in improving the LEAN process by focusing on value and reducing waste. In addition, waste, temporary or supporting elements, and upstream construction materials are all connected to construction parts; these data could become part information and form a complete value stream of construction parts.

**Summarizing key properties of construction parts**

To answer this paper’s research question, a construction part was defined as any entity that requires
an act of installation to become a component in the final building product. This definition is consistent, value-focused, and quantifiable. It defines a part by its physical nature (entity), required action (installation), and final condition (a component in the final building product). Waste, temporary, supporting, and upstream construction materials are not construction parts. Figure 1 illustrates some examples considered to be construction parts and others that are not in the context of the AEC industry. One part is counted when it is installed in the building as one piece. Discrete and non-discrete categories help with construction part quantification. Construction part quantification is guided by working cycles or installation procedures; one part is installed in one construction working cycle. With the definition of a part and the ways to quantify construction parts given herein, it is possible to count the total number of construction parts in a building project.

![Figure 1: Examples of Construction parts and what is NOT Construction parts](image)

**Case study to apply the definition of construction parts**

Using the operational definition of a construction part, the research team conducted a case study to validate the use of the construction parts concept on an actual construction project. The objectives of this case study were:

- To validate the quantifiable criteria necessary for a “part” definition
• To verify the operational definition of a construction part and its quantification rules.
• To explore a part counting methodology for a project in the design and early construction phase.

Application procedure

The project is a seven-floor luxury hotel with 420 guestrooms in Shanghai, China. It has a gross floor area of approximately 40,300 m². The hotel was in its early construction phase at the time of this case study. The study focused on the hotel building itself, from foundation to rooftop. Construction beyond the building boundary, such as parking lots and roads travelling toward the hotel, was not included. This case study used 60% CD BIMs (3D models at the 60% Construction Documents phase), drawings of typical hotel sections, and some construction material specifications as major information sources.

Hotel BIM

The 60% CD BIMs were key reference data source; they contained the major architecture, structure, MEP, exterior skin, and interior detail elements of the hotel at approximately the LoD 300 level. When generating a list of BIM elements from these models, the 60% CD BIMs contained about 110,000 virtual elements, of which around 98,000 were physical elements and 12,000 were analytical elements (such as grid lines, room tags, etc.).

These BIMs and BIM elements imply two facts. First, the 60% CD BIMs do not contain all project construction parts. For example, many electrical fixtures, furniture, and equipment were not modeled in the BIMs, as well as small connecting construction parts such as hangers and screws.
Second, physical elements in the BIMs do not have one to one relationships with construction parts in construction. In some cases, one BIM element represents multiple construction parts. For example, the concrete slab for an entire floor was modeled as one piece in the BIMs whereas during construction it may take multiple pours, that is more than one part. In other cases, multiple BIM elements were actually one part. For example, a tee duct that would be manufactured and installed as one piece was represented as three separate pieces in the BIMs.

Although the BIMs were still under development at the time of this study, it was certain that even a completed BIM would not have been an accurate virtual representation of the number of construction parts in this hotel project. Other drawings and material specifications are used in the project, but not all existing documents were available to the author, and some available drawings were outdated and inaccurate. Further, the construction team was just starting to specify the construction methods, which had a great influence on the total number of construction parts because a prefabricated building element would have much fewer construction parts than the same element built on-site.

Since the project was ongoing and the existing documents were limited, some assumptions, were made to account for the missing information.

**Assumptions**

Three main assumptions were made: (1) high and low estimates of construction parts count in different building elements, (2) using one typical element or area to represent similar elements or areas; and (3) the assumptions about construction parts in sections or components with no BIM or
documents.

**Determining construction methods**

According to the construction parts quantification method described above, materials installed in the building on-site in one cycle are one part. Because most of the construction methods for the hotel were not determined at the time of this study, the research team made assumptions based on professional judgements on how various building components would be installed. In other words, these assumptions were based on existing design and typical construction approaches as consulted with industry professionals.

The team provided a range on the number of construction parts through high and low estimate for each construction element, such as a window, lamp, or bathroom sink. The high estimate assumed that many construction parts were delivered and constructed on site as in-situ materials, while the low estimate assumed that the construction parts were assembled off-site and delivered to the construction site as one piece as much as possible. These construction elements were identified using BIMs and other drawings. The high and low estimates were then made based on existing documents and typical installation manuals for similar elements found on the Internet.

For example, the high estimate of a door assembly assumed that the door panel, hardware, and frame were to arrive separately and are assembled on site (Figure 2). Because all construction parts were to be installed inside the building at their final location, each jamb was considered a single part, and each screw attaching the frame to the wall was also considered a single part. On the other hand, for the low estimate, this same door was assumed to be a pre-hung door assembly that arrives
with door panel, three hinges, and frame already assembled and was counted as one part. Note that each screw needed to attach the frame to the jamb was still considered a single part. As a result, this door could have 19 to 46 construction parts depending on the installation method used.

Figure 2: High and Low Estimate of the Number of Construction parts in a Typical Door Element

The estimates did not assume complex or large-scale prefabrication since the project did not have such a plan. For special elements, such as movable chairs, the high and low estimates were the same; in this case, they were both one part. For other elements, this assumption created a construction parts range for each element, and it was with high confidence that the actual construction parts count for installing that element falls in this interval. This assumption was applied to each typical construction element, resulting in a range for the total number of construction parts in the final building product.

*Inferring construction parts from repeated modules*
Architects typically designed hotel building elements to be similar or repeatable, such as glass panels, foundation piles, and floor tiles. Many areas in the hotel project were also similar or identical, such as standard guestrooms, staircases, and elevators. Therefore, it was possible to use the number of construction parts for certain elements or certain areas to estimate the number of construction parts for other similar elements or areas.

A series of assumptions were made to use the number of construction parts from one typical module to infer the number of construction parts for similar modules. The modules were as simple as a door or as complex as a guestroom. Some modules were certain areas or certain lengths, such as one square meter of ceiling tile or two meters of ventilation pipe. BIMs and drawings were used to calculate the number/area of the repeatable modules in certain sections of the building. Then the research team used the high and low part estimates to compute the range of part counts in each typical module.

For example, take one ceiling tile as a module (Figure 3). The installation of one ceiling tile required 10 (low estimate) to 24 (high estimate) construction parts, and the tile had an area of 1.44 m². Thus, for a 20 m² ceiling with this type of tile, the total number of construction parts was 139 (10×20/1.44) to 333 (24×20/1.44). This assumption often ignored the different module details at the boundaries as they are assumed to be insignificant given the detail available at the time of the study. For example, the ceiling tile at the edge of the room would likely be different from a typical tile; therefore, it would have a different number of construction parts. But in this study, they were assumed to be the same because the design had not yet reach this level of detail. Similarly, when a standard guestroom was used as a module; other standard guestrooms had the same construction
parts range as the module room. The construction parts range for the module room was calculated by adding up the estimation of all elements in the room. In this case, although standard guestrooms on different floors were slightly different in size or orientation, they were assumed to be the same, whereas family rooms or luxury rooms were not the same and were estimated separately.

\[
\begin{array}{c|cc}
\text{High} & \times 4 & \times 4 \\
\text{Low} & \times 4 & \times 4 \\
\hline 
\text{Hanger Rod} & \\
\text{Hanger Fastener} & \\
\text{Main Keel} & \times 2 \\
\text{Fasiener} & \times 4 \\
\text{Furring Keel} & \times 2 \\
\text{Panel} & \times 4 \\
\text{Painting} & \times 4 \\
\end{array}
\]

**Figure 3: Using the Number of Construction parts in a Typical Ceiling Tile Module and Floor Plan Area to Estimate the Number of Construction parts in the Room Using the Same Type of Ceiling Tile**

*To account for unknown sections and components*

The detailed designs of several hotel sections were not available for the case study, such as the kitchen, swimming pool, gym, etc. In addition, building components such as sprinklers, security cameras, and detailed lighting fixtures for the whole hotel were not available as well.

To account for the unknown sections, the authors selected sample areas in the hotel that serve similar functions and had more available documents. Then the authors assumed the unknown
sections to have the same construction parts quantity as their matching sample areas. Hence, the construction parts counting results of the sample areas can act as an estimate for the number of construction parts in unknown areas.

The part density was determined per square meter. For example, the kitchen area was assumed to have the same construction parts per square meter as a typical mechanical room, and the dining area had the same construction parts density as the office area. Therefore, even without layout of cooking devices or dining tables, it was possible to estimate the number of construction parts in those sections. However, the structural components, ceiling, floors, and doors were not included in the construction parts density estimation; they were instead, counted according to floor plans. To account for the unknown components, some of them were estimated using typical construction details from the Internet, such as lighting fixtures; others were not included in the construction parts count, such as sprinklers and security cameras.

In general, these assumptions have high uncertainties owing to the lack of detailed information in traditional methods. Because of these unknown sections and components, it is likely that the hotel’s construction parts count was lower than the actual number.

**Counting procedure**

Given the above assumptions, the actual counting procedures are being developed. Figure 4 illustrates the flow of the established process. Overall, the whole process of the aforesaid study took about four months with seven graduate and undergraduate students working part-time (average two days per week).
Figure 4: Procedure for Counting Construction parts in Four Steps and Assumptions in Each Step

To start with, the team took UniFormat as a guideline to divide the building into five systems: substructure, shell, interiors, services, and others (anything in the BIMs that does not belong to the previous four systems). First, all construction parts in the substructure system of the hotel were counted and then all construction parts in the shell systems. For the rest of the building, construction parts were either grouped by space (mostly guestrooms) for counts, or counted by UniFormat systems (interiors, services, and others) and sub systems. For example, major plumbing pipes were counted as part of the services system, yet the small plumbing fixtures in each guestroom were grouped into guestrooms and counted together with other construction parts in that guestroom.

After the building was broken down to systems or spaces, the team identified the type and number of different building elements in each system or space. Then, a high construction parts-estimate and a low construction parts-estimate were determined for each element. The construction parts range for a system or space was calculated by adding all elements’ ranges together. The whole building’s construction parts range was calculated by adding all the systems’ and spaces’ construction parts estimate ranges together.
The research team worked in pairs when counting each system and general guestroom spaces. Weekly or bi-weekly meetings were held to cross-check each other’s result and set up work plans. The major amount of effort was spent on calculating the number of repeated modules by reading BIMs and drawings, and getting the high and low estimate of certain elements using typical installation manuals found on the Internet. This was mainly due to the lack of information provided by designers and contractors on the actual type of elements used and the installation method of those elements respectively. More precise counts are expected if more information were available.

Application results

This section discusses the results for the case study, which are: the total number of construction parts in a building project; whether the operational definition of a part and construction parts quantification rules work; and the construction parts counting methodology for a project in the design and early construction phases.

Estimated hotel construction parts range

The 420-guestroom luxury hotel project in Shanghai had an estimated range of 3.2 million to 4.6 million number of construction parts (Figure 5). This estimate was based on the 3D models at the 60% Construction Documents phase documents and covered five main building systems: substructure, shell, interiors, services, and others. Note that due to the assumptions described in the above section, this result has a low confidence level. Considering the unknown building sections and components, the hotel’s actual number of construction parts could be much higher.
Figure 5: Hotel Construction parts Breakdown with High and Low Estimates for Five Building Systems; the Total Number of Construction parts is 3.2-4.6 Million

Yet this construction parts range still illustrates several points. First, due to the many interior decorations in the hotel, the interiors system has the largest number of construction parts: 1.7 to 2.5 million. Second, both interior and shell systems’ part ranges have large variations. It is because these construction parts have a better potential for prefabrication. Therefore, they have larger variance in the number of construction parts. Finally, it was estimated that roughly 50% of the hotel’s construction parts are various connectors/fasteners, such as nails, studs, bolts, etc. Although these connectors/fasteners were not included in the BIMs or design documents, it is highly likely that they will take a considerable amount of labor hours to be built on site. This lack of detail as seen in BIM can be reflected by the concept of construction parts, as hypothesized.

Case study takeaway

The case study covered five main building systems and recognized millions of construction parts.
It confirmed that this operational definition of a part is able to identify most building elements in a typical building project even without accurate final documentations. Also, the discrete and non-discrete part categories and their counting methods have proven effective in quantifying all construction parts encountered in this case study. Therefore, the case study confirmed the generality of the construction parts research: both the operational definition of a part and the quantification methodology apply to general building projects.

The authors have explained the importance of the fundamental unit to be irreducible in order to represent the values at work face more effectively. This case study has demonstrated that the construction parts count in the early construction stage has a low confidence level, which confirms the limitation brought up in our existing system: the project drawings and BIMs are not deterministic when it comes to construction parts. Since construction parts are usually linked to construction details, these unattended construction details increase the uncertainty of project quality in earlier phases of a building’s lifecycle. For example, while there were more than 3.2 million construction parts in the hotel project, there were only 98,000 physical BIM elements in the model, around 3% of the total number of construction parts. Therefore, it is hard to manage the 3.2 million construction details when only 98,000 elements are identified. Even in the construction phase, it is unlikely that the drawings contain enough information to guide the installation process. Submittals and shop drawings may include most construction parts, or may not when it comes to non-discrete construction parts such as glue, spray, or tape. This problem can have a huge negative impact on project performance. Because the drawings cannot guide installation, the individual elements’ construction methods and steps are often worked out on site based on knowledge from one particular discipline, or the experience of a particular craftsmen. The overall construction
process is then isolated as disciplines operating on their own, and there is little time for integration and optimization due to the tight on-site schedule. In addition, since design focuses on the system or trade level and construction focuses on the construction part-level, design and construction are disconnected. This gap affects the overall management and information flow between parties and through phases. As project performance is greatly influenced by construction parts’ installation quality and quantity, it is very hard to ensure good project performance without knowledge and control of all the building construction parts. With this newly defined unit that is irreducible, consistent across all disciplines and representing the values at work face, practitioners can establish a common platform for seamless information flow and communication.

In addition, this case study also illustrates the consistency and quantifiability of construction parts, since construction parts count is taken at the project level, aggregating across all disciplines. This feature of construction part allows performance metrics to be build based on this unit as defined such that industry practitioner can improve their management means through construction parts-related metrics. For example, complexity of the project based on the average, high or low estimates of parts count, modularity improvement potential using the difference between high and low estimates of the overall project or at each system can be potential metrics based on the concept of construction parts.

In summary, to test the proposed construction parts concept, a part counting case study was conducted on a hotel project. The results show the generality of the operational definition of a part and the construction parts quantification rules. The definition of a construction part can be used to describe input products in building projects. The construction parts quantification rules should give
a consistent number of construction parts when construction methods are known. The results also show that drawings and BIMs are not deterministic when it comes to construction parts. When estimating the number of construction parts in a project using drawings and BIM before construction starts, one needs to make some assumptions.

Discussion

The definition of a construction part enables AEC practitioners to have a shared fundamental unit of measure for building input products and a common way to communicate and quantify states and performances of building construction projects across different trades and projects. This is the first step of developing a construction parts concept that is applicable to project designers, engineers, operators and developers. This section discusses some future research directions, which extend the definition of construction parts to enhance their benefits for the AEC industry.

Automated estimation of the number of construction parts

As described in the previous section, it took several months to count the number of construction parts in the hotel project. The difficulty for identifying construction parts with only design documents lies on the insufficient data stored in design documents. Therefore, it could be hard to quantify the potential impact of different design options on construction parts and project performance. To mitigate this problem, it is proposed to develop a specification to make construction parts quantification fast and easy, ultimately into a set of logics that supports automatic construction parts counting. In the long run, construction parts specification may be incorporated into BIM software, making automatic construction parts estimate with BIM possible.
Construction parts ontology

An ontology for construction parts is required to manage the construction process of a building project. Ontology is an “explicit specification of a conceptualization”; it defines the concepts, classes, relationships, and other distinctions about a certain knowledge domain (Gruber 1993). Using the ontology will allow incorporation of manufacturing strategies at the construction parts level and be used to monitor and control the construction progress. In the long term, the AEC industry should not only use the construction parts concept to manage construction process but also to optimize project design and construction and select the best strategies to improve project performance and productivity.

Construction part-related information

Although temporary construction works, such as formwork and scaffolding, do not fall into the definition of a part, in some cases, these works contribute a significant portion to a building’s cost and duration. It is estimated that formwork of the concrete slabs in the hotel case study may constitute up to 20-35% of the total material and labor costs for the concrete slab work. To solve this problem, it is proposed to link information about temporary work and waste to construction parts as attributes. For example, the information about the geometry configuration and the actions on the concrete slab supports a project team in selecting the appropriate temporary formwork (Kim and Fischer 2006).

As for earthworks, it can be noted as preparation for the entire project or certain sections of the project. Therefore, construction part-related information will include direct information, such as material and labor cost, schedule, etc., and indirect information, such as required temporary work
and other supportive construction activity. If that information would be formally represented, it could help quantification and reduction of temporary work and waste on projects.

**Conclusion**

The lack of knowledge and attention to building construction parts in the pre-construction phase limits improvement of productivity in the AEC industry. In comparison, the manufacturing industry uses detailed part information throughout a product’s lifecycle to improve its production. Since the two industries are similar in that they both produce a final product for their customers, as our first step, understanding construction parts in the AEC industry are hypothesized to improve the effectiveness of project management. However, since current AEC industry standards do not support a definition of a part in building projects, it is hard to capture or utilize part-based building information in AEC projects.

Therefore, this paper focused on defining and quantifying construction parts in a building project as the first step of establishing the construction parts concept in the AEC industry. The authors proposed the operational definition of a part as “any entity that requires an act of installation at work face to become a component in the final building product”. This operational definition of a part emphasizes the direct value-adding activity, which is the final physical installation activity. According to the definition, construction parts can be as big as girders, rebar cages, and prefabricated assemblies or as small as nails, studs, and bricks. However, waste or spare products, temporary construction materials, supporting elements, and equipment or tools are not construction parts.
To estimate the number of construction parts, this paper introduces discrete and non-discrete part categories. For discrete construction parts, one part is counted as one if it is installed to the building as one piece; for non-discrete construction parts, one non-discrete part is determined by a complete working cycle. How much material the construction crew installs or applies to the building in a working cycle becomes an important attribute of non-discrete construction parts. Using the working cycle approach to identify a part ensures that the total number of construction parts in a project is reasonably assessed.

To see if the proposed definition of a part was useful, a case study was conducted on a seven-floor luxury hotel with 420 guestrooms to estimate the total number of construction parts in the project. The results showed an estimated range for the number of construction parts from 3.2 to 4.6 million, covering five main building systems: substructure, shell, interiors, services, and other. The counting process was based on 60% Construction Documents phase documents and BIMs and contained various assumptions and simplifications. Therefore, the result had a low confidence level and the hotel’s actual number of construction parts was expected to be much higher. The case study confirmed the generality of the operational definition of a part and the construction parts quantification rules.

From the case study, the authors summarized a methodology to estimate the number of construction parts in a project in the early construction phase; the major steps are: break down the building to similar systems or spaces, use drawings and BIMs to identify building elements, make high and low estimates of the construction parts required to build each element, calculate the total number of construction parts by adding all the systems’ and spaces’ construction parts estimate
ranges together.

The fact that the authors had to make assumptions and simplifications in the case studies shows that the project drawings and BIMs are not deterministic when it comes to construction parts. That is, the drawings and BIMs do not contain detailed construction part information or enough information to guide the installation process, leaving the detailed construction methods to on-site judgments that are often not well integrated. In addition, since drawings are not down to details at the construction parts level, it is difficult for a project engineer to optimize project delivery (based on drawings and BIMs) with construction process taken into consideration. The AEC industry will need to pay more attention to construction parts in the design phase in order to better control and optimize the construction process.

This paper emphasizes the importance of construction parts and defines a construction part. To make the construction parts concept applicable to the industry, future study includes development of a construction parts counting specification, formulation of construction parts’ ontology, and formalization of part-related information. These will allow practitioners in the AEC industry to develop better methods for managing construction projects, optimizing design and construction, and improving project performance and productivity.

**Acknowledgements:** The authors would like to express sincere thanks to the faculties and members from Stanford Center for Integrated Facility Engineering (CIFE) for their constant guidance and support. The authors would like to thank the industry participants for their contributions and case studies, the researchers from Stanford University, Tongji University, and
other universities. The authors would also like to acknowledge the inputs of the students who enrolled in CEE 112/212 at the Department of Civil and Environmental Engineering of Stanford University in 2012, 2013, and 2014.

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