An Analytical Method to Estimate the Total Installed Cost of Steel Frames during Early Design

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Abstract: This paper presents a method to quickly and accurately estimate steel frame material, fabrication, and erection cost based on early design information. The proposed method utilizes a secure web portal that enables suppliers to provide current unit cost data. The method also includes an automated connection detailing component that provides the quantities required for a detailed steel frame cost estimate based on the unit rates provided by the supplier. We apply the estimation method to a simple moment frame and illustrate the difference between a frame designed for least-weight of steel, and one designed for least cost. The results show that the least-cost frame realized a 14% cost savings over the least-weight frame while adding 7% to the total steel tonnage. These initial results demonstrate the potential of the method to improve early stage design decision-making through better vertical integration of project information in the AEC industry.

Highlights:

- Analytical cost estimate based on early design information
- Automated connection detailing of steel frame structures
- Web portal allows steel suppliers to maintain current cost data
- Cost data visualization in the context of the BIM

Key Words: Steel frame; detailed cost estimate; automated connection design; cost optimization; BIM

1. Introduction

Decisions made early in the structural design process are critical to delivering safe and economical building and civil structures. The major phases of the process include: early design, design development, and connection detailing. Typically, the frame type (e.g., moment frame, braced frame) and general layout of structural members is performed during early design. The member cross sections are defined or "sized" during design development. Finally, the connections between members are designed during the connection detailing phase. It is estimated that 37% of the total installed cost of steel frame structures are determined during early design and that 63% of costs are determined by the completion of the design development phase of the project [1] as illustrated in Figure 1.

Conventional practice during early design and design development is to estimate the total installed cost of the structure based on the weight of steel used. Skitmore and Ashworth define this as an approximate estimate since it relies on a single variable, i.e. the required weight of the steel members [2]. The most significant drawback to a weight-based approximate estimate is that the total installed cost of a steel frame is not a linear function of its weight, but rather consists of three primary components: material, fabrication and erection. Material costs are typically only 25-40% of the total installed cost for a steel frame – the majority of costs are associated with fabrication and erection. Fabrication encompasses the cost of processes that take place in the fabricator's shop (e.g., cutting, welding) while erection costs include all field expenses required to build the

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Figure 1. The definition of steel frame costs as a function of project phase [1]. The proposed method enables analytical estimates to inform early design decision before the majority of costs have been defined.

Figure 2. Typical distribution of the total installed cost of a steel frame [4].

Therefore, weight-based approximate estimates can support design decisions which lead to lighter, but more expensive structures [5].

Typically, steel fabricators create a more accurate analytical cost estimate of the structure when they become involved in the project, after construction documents are complete and put out for bid. The analytical estimate is based on a bill of quantities of all material elements and work items for the construction of the steel frame with associated unit costs for each quantity [2]. The quantities are based on engineered connection details. These quantities can be tallied manually within spreadsheets, created within a commercial fabrication estimation application (e.g. FabTrol, FabSuite), or extracted directly from the Building Information Model (BIM).

However, since fabricators typically do not get involved until the Connection Detailing phase of the design process, it is difficult for their input to inform design decision-making. Paulson notes that “once the decision has been made and design has progressed, it is disruptive and generally abortive to make fundamental changes to the frame type or form” [6]. The lack of accurate cost information to inform early stage design decisions has been discussed in several other publications, e.g. [7–9].

As championed by MacLeamy, this paper seeks to make information available early in the design process when it is most impactful [10]. To this end, we propose the development of an analytical cost estimation method that can be
used by engineers during the early and design development phases of the project, before the majority of the cost of the structure has been defined (see Figure 1). The following requirements have been identified for such a method:

1) **Comprehensive**: Including material, fabrication, and erection costs of the steel frame.

2) **Current**: The cost components for steel frame structures can change rapidly with market conditions [11], thus, it is important that the estimation method be easily updated to reflect current cost data.

3) **Based on early design information**: Including just member centerline geometry and connection type specification, as a detailed bill of quantities based on connection detailing is typically not available early in the design process [12].

4) **Low-latency**: Engineers quickly explore many different structural layouts and sizing alternatives early in the design process and require near real-time cost feedback to effectively inform decision-making [13].

The outline for the remainder of this paper is as follows: Section 2 provides some background on existing cost estimation methods for steel frames. Section 3 describes the proposed analytical cost estimation method which leverages data provided by steel mills, fabricators and erectors. In Section 4, we demonstrate the use of our proposed method with an example problem. Finally, Section 5 presents the conclusions and discusses the future work for the research. The appendix tabulates the list of rates and preferences used for our example problem.

2. **Background in Cost Estimation of Steel Structures**

The reliance on weight-based estimates for structural optimization is represented in much of the literature; [14–17] provide a small sample. The limitations of this approximate method for cost estimation of steel frames is discussed in the previous section.

Xu and Grierson [18] extended the weight-based estimation approach with an added weight to represent the cost of the connections between steel members. The weight added was linearly dependent on the connection’s rotational stiffness. Many studies have used this estimation method to assess the cost of frames with semi-rigid connections [19–21]. This method does not provide a detailed analytical cost estimate, but can be characterized as an expanded approximate cost estimate which doesn’t capture the cost implications that are independent of rotational stiffness.

Several studies present analytical cost estimation methods based on fabrication and erection costs [22–24]. These studies examined several categories of fabrication operations and developed regression functions for the cost of each category. Each of these relied on dozens of cost and time factors, that in turn relied on thorough data input to select appropriate parameters for the regression functions. While the reviewed methods include detailed fabrication and erection rates, material is assumed to be constant price per unit weight. The ability to input a different price for each section size as provided by steel mills or distributors is not provided. Also, these methods require a complete bill of quantities, including quantities resulting from connection detailing. As noted earlier, detailed connection quantities are not typically available during early design.

Bel Hadj Ali et. al. [9] calculated steel costs based on a cost method developed by Hamchaoui [25] updated for semi-rigid connections. The method calculated fabrication costs by querying a database of average process times for individual components of fabrication. These rates were obtained by interviews and by timing activity durations for components as they moved around a typical fabrication shop.
They avoided major erection cost differences by limiting the scope to bolted connections and priced erection activities as a function of steel weight. This method also requires a detailed bill of quantities that is typically not available early in the design process.

The analytical costing methods described above all achieved a degree of accuracy beyond what is possible using approximate weight-based estimation. However, none of the reviewed methods compiled accurate material costs or are able to provide an estimate based on early design information.

3. Method
The proposed analytical method is able to provide comprehensive and current cost estimates for steel frame structures based on early design information. The method relies on a web portal and several cloud-based processes to achieve this as illustrated in Figure 3.

The web portal enables design engineers and steel suppliers, including the mill, fabricator and erector, to each input their respective data in a private and secure environment. Automated structural analysis and detailing operate on the early design data provided by the designer to develop a comprehensive bill of quantities required for the analytical cost estimate.

Finally, the results are visualized with minimal latency for the designer in the same web interface. Each component in the proposed method is described in detail below.

3.1 Frame Data
The designer uploads their frame data via web portal from any platform they use for modeling. This could be a BIM or the analytical model for structural analysis, and contains the geometry, material, and connection data available during early design. The frame data may also include the frame forces and displacements resulting from the structural analysis, or just the structural loads. The difference is only whether the structural analysis is performed by the designer locally, or within the estimation method in the cloud.

3.2 Unit Prices / Preferences
Mills, fabricators and erectors can use the web portal to securely maintain current price rates and detailing preferences (see Figure 4 for a screenshot of the web portal).
Table 1. Detailing Quantities

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Members</td>
<td>Size, grade, and type of steel sections</td>
<td>W10x60 x 30ft column, grade A992</td>
</tr>
<tr>
<td>Plates</td>
<td>Size, grade, and type of steel sections</td>
<td>9” x 9” x 5/8” Continuity Plate, grade A992</td>
</tr>
<tr>
<td>Cutting Operation</td>
<td>Size, and type of cutting</td>
<td>4” length of CNC access hole in 3/8” thick web</td>
</tr>
<tr>
<td>Weld Prep</td>
<td>Volume of material to remove</td>
<td>1.5in³ of steel removed to bevel beam flanges for CJP</td>
</tr>
<tr>
<td>Holes</td>
<td>Number, size, and type of holes produced in metal</td>
<td>(3) 7/8” dia holes punched in 3/8” plate</td>
</tr>
<tr>
<td>Welds</td>
<td>Size and type of welds</td>
<td>0.27in² weld area x 10” weld length, CJP, shop weld</td>
</tr>
<tr>
<td>Bolts</td>
<td>Size and type</td>
<td>3/4” dia x 3” length, A325, pretensioned</td>
</tr>
</tbody>
</table>

The web portal allows the user to specify what data is visible to project collaborators. The fundamental unit rates for fabrication and erection are listed in Table A in the appendix and is based on a review of fabricator and erector analytical cost estimation procedures. The detailing preferences are also located in Table A and specify parameters that are not prescriptive in the governing code or may result from concerns other than code compliance, e.g. weld root dimensions, minimum bolt diameter.

3.3 Structural Analysis
Our workflow currently includes a separate nonlinear frame analysis prior to the detailing, to calculate the required frame forces and displacements from the frame data. The analysis also flags members or displacements that exceed strength or serviceability limits.

3.4 Automated Detailing
This component automatically designs the connections between members in order to produce a bill of materials suitable for analytical cost estimation. The detailing algorithm receives the complete frame dataset and applies the code specific tasks for the defined connection type to quantify the total counts, specifications, dimensions and geometry of all connection elements (see Table 1). Additionally, the algorithm checks any geometric constraints for a particular connection type; this is relevant to the seismic provisions of AISC 341 and AISC 358 [26,27].

The detailing component loops through all nodes of the frame that require one or more connections, detailing all member connections at that node simultaneously. The connection elements are prescribed to a particular connection by applying the appropriate logic for the specified connection type. Any number of connection types can be parameterized and codified into the detailing algorithm. Fabricators and designers utilize similar libraries of parametric typical details that readily integrate into our estimation method. Figure 5 illustrates the detailing flowchart for a WUF-W (welded unreinforced flange-welded web) prequalified IMF (intermediate moment frame) connection from AISC 358 [27]. Figure 8 in the subsequent section shows an example of a connection detail with these elements annotated from our example problem. The connection quantities are then passed to the cost function.

3.5 Cost Function
The cost function multiplies connection quantities with the corresponding rates maintained through the web portal. The cost data is structured so that the costs for the individual components for each category (i.e. material, fabrication, and erection) are attached to those components. The function also aggregates the costs for the frame or any compilation of costs preferred by the designer.
Figure 5. Example automated detailing process for WUF-W IMF connections.

See the results from our example problem in the following section (Figure 7) for costs aggregated by connection and member, with subcategories specified. The cost calculation can be made for any number of suppliers, or average the unit rates of a specified subset of the suppliers. It is important to note that the fidelity of the engineering required for an estimate is much less than required for final construction documents.

3.6 Output Visualization
The resulting detailing and cost data are sent back to the web portal to visualize the cost data in a manner that the designer can customize to meet their needs. Again, refer to Figure 7 for an example visualization of a bar chart breakdown of costs for a selected member and connection. Similar break downs of all members and connections are available to any granularity preferred by the designer. The connections are highlighted in yellow to draw attention to the designer. The corresponding warning notifies him or her that these particular connections require additional elements that increase fabrication costs. See [28] for a detailed discussion of the possibilities for cost visualization.

4. Example Problem: 1x1 Frame
This example problem demonstrates the use of the estimation method and illustrates the difference between frame section sizes that are chosen for least weight versus least cost.

4.1 Problem Description
Our example frame is a one-bay, one-level (1x1) moment frame. See Figure 6 for a description of the frame geometry and loading. The type of moment connection used is a WUF-W IMF connection.

The beam size is limited to the AISC W410 family, and columns limited to the W200 or W250 families. The drift ratio is the controlling
limit state, and is equal to 1/300 (ratio of lateral translation over story height).

4.2 Method Implementation

The proposed analytical estimation method was applied to the 1x1 frame problem described above. This frame was detailed with the WUF-W IMF connection type. The detailing component creates all connection elements shown in Figure 8. Initially, we selected the frame section sizes from the defined range for least weight, while satisfying the constraints of drift ratio limit and strength limits of AISC 360. When selecting sizes for least cost, the objective was to minimize the total cost per our estimation method while satisfying the constraints. Every possible combination of beam and column member sizes was evaluated in order to identify the least-weight and least-cost design alternatives.

4.2 Results

When we select member sizes for the least-weight of steel while satisfying the constraints, the beam size is W410x67 and the columns are W250x101. The resulting frame weight is 0.97mt and total cost is $4,272. When choosing member sizes with the minimum cost, the beam size is W410x46.1 and columns are W250x131, for a frame weight of 1.05mt and total cost of $3,818. The results for the least-weight and least-cost design alternatives are summarized in Table 2.

The components of the connections for the least-weight and least-cost frame are shown in Figure 8 with differences annotated. The heavier column sections in the least-cost solution meant the labor-intensive continuity plates were no longer necessary to stiffen the flanges. The heavier column sections also provided more stiffness to the frame, which allowed a lighter beam section to offset some of the added weight while still meeting the drift ratio criterion. See Figure 7 for a breakdown of the cost data for the least-weight design alternative.

The time to perform the structural analysis and apply the estimation method for this simple frame was 0.2 sec on a standard laptop having 3GHz processor and 8GB ram. The structural analysis required 90% of that time, with the remaining 10% to detail the connections and calculate the cost. To analyze and price each of 308 possible scenarios (28 possible columns and 11 possible beam sizes) the time was 50 sec.

<table>
<thead>
<tr>
<th>Minimum Weight</th>
<th>Minimum Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Size</td>
<td>W410x67</td>
</tr>
<tr>
<td>Column Size</td>
<td>W250x101</td>
</tr>
<tr>
<td>Frame Weight</td>
<td>0.97mt</td>
</tr>
<tr>
<td>Material Cost</td>
<td>$1241</td>
</tr>
<tr>
<td>Fabrication Cost</td>
<td>$1350</td>
</tr>
<tr>
<td>Erection Cost</td>
<td>$1681</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$4272</td>
</tr>
</tbody>
</table>

Table 2. Comparison of least-weight and least-cost design alternatives for 1x1 frame.
5. Conclusions

This paper presents a new analytical method to quickly and accurately estimate the total installed cost of steel frame structures based on early design information and leveraging current supplier cost data. To achieve this, the method utilizes a web portal that enables design engineers and steel suppliers, including mills, fabricators and erectors, to each input their respective data in a private and secure environment. Automated structural analysis and detailing components operate on the early design data provided by the designer to develop a comprehensive bill of quantities required for the analytical cost estimate. Finally, the results are visualized with minimal latency for the designer in the same web interface.

The method is demonstrated on a 1x1 example frame to illustrate the difference between a frame designed for least-weight of steel, and one designed for least cost. The results show that the least-cost frame realized a 14% cost savings over the least-
weight frame while adding 7% to the total steel tonnage.

The significant cost savings achieved by least-cost design compared to the least-weight design demonstrate the potential benefits of providing accurate analytical cost feedback to designers early in the process when there is a relatively high level of design freedom. Further industry applications will be required to comment more generally on the performance and robustness of the proposed analytical estimation method compared to approximate methods commonly used by design engineers in practice today. The example application in this paper included a limited number of member sizing variables (beam and column) and only allowed for a single connection type (WUF-W). Additional applications are planned to test the impact of the method on larger structures with more design variables.

As acknowledged in the literature, many of the unit cost data inputs to the estimation method are characterized by different levels of uncertainty. Further research is planned to model this uncertainty and to replace the resulting cost output with a probability density function (PDF) instead of a deterministic value. Additional areas of continued research for this project include:

- Expand the scope to include additional connection and frame types (to included semi-rigid connections), foundation costs, and more-sophisticated erection pricing.
- Refine and validate the list of fundamental rates across the expanded scope with the participation of more fabricators and erectors.
- Incorporate supplemental metrics of schedule and environmental impacts.
- Include life cycle pricing with expected damage using performance-based design.

The authors expect that this continued research will enable designers to make better decisions and that it will demonstrate the value of improving vertical integration of project information in AEC industry. Fundamentally improving the design process in this way will promote design innovation by making it easier to analyze and iteratively improve new design concepts based on current and accurate cost data provided by the product supply chain. Ultimately, this will result in higher quality and more economical buildings for the public.

Acknowledgements

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References


## Appendix

### Material Element

<table>
<thead>
<tr>
<th>Material Element</th>
<th>Rate</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide Flange Sections</td>
<td>section dependent</td>
<td>Material costs are dominated by the cost of the steel sections. Based on a snapshot of one mill's prices, from $770 to $1160/tonne.</td>
</tr>
<tr>
<td>Steel Plates</td>
<td>$1460/tonne</td>
<td>Price rates can be input for plates of different grade and size</td>
</tr>
<tr>
<td>Shop Weld Material</td>
<td>$4.97/kg</td>
<td>Price rates can be input for different types of consumables, based on the weight of the nominal amount of weld material.</td>
</tr>
<tr>
<td>Field Weld Material</td>
<td>$8.48/kg</td>
<td>Price rates can be input for different types of consumables, based on the weight of the nominal amount of weld material.</td>
</tr>
<tr>
<td>Bolts</td>
<td>$3.77/kg</td>
<td>Price rates can be input for bolts of different grade and size</td>
</tr>
</tbody>
</table>

### Fabrication Element

<table>
<thead>
<tr>
<th>Fabrication Element</th>
<th>Rate</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shop Labor</td>
<td>$60/hr</td>
<td>All fabrication processes are given rates of time, and those times are multiplied by one cost rate for the shop.</td>
</tr>
<tr>
<td>Section Handling</td>
<td>66min/tonne</td>
<td>Minutes of shop time to move the sections around the shop.</td>
</tr>
<tr>
<td>Section Sawing</td>
<td>0.5min/cm²</td>
<td>Minutes to cut sections to length with band saw, sawing both ends of each member.</td>
</tr>
<tr>
<td>CNC Cuts</td>
<td>2.0min/cm</td>
<td>Minutes to cut access holes or slots in sections, per length of cut.</td>
</tr>
<tr>
<td>Beveling</td>
<td>0.6min/cm³</td>
<td>Minutes to remove material for bevels in preparation of welds.</td>
</tr>
<tr>
<td>Holes</td>
<td>2.0min/hole</td>
<td>Minutes to punch holes.</td>
</tr>
<tr>
<td>Plate Handling</td>
<td>30min/plate</td>
<td>Minutes to move the plates around the shop and layout operations.</td>
</tr>
<tr>
<td>Plate Cutting</td>
<td>0.8min/cm</td>
<td>Minutes of shop time to cut plates to size, per length of cut.</td>
</tr>
<tr>
<td>Shop CJP Welds</td>
<td>45min/kg</td>
<td>Minutes to weld CJP connections per nominal weight of consumable.</td>
</tr>
<tr>
<td>Shop Fillet Welds</td>
<td>0.2min/cm</td>
<td>Minutes to weld fillet connections up to a maximum leg size of 8mm.</td>
</tr>
</tbody>
</table>

### Erection Element

<table>
<thead>
<tr>
<th>Erection Element</th>
<th>Rate</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Labor</td>
<td>$90/hr</td>
<td>All erection processes are given a single rate for field time.</td>
</tr>
<tr>
<td>Lifting</td>
<td>60min/piece</td>
<td>Minutes of field time to lift members into place.</td>
</tr>
<tr>
<td>Welds (by weight)</td>
<td>14min/kg</td>
<td>Minutes to weld in the field, per nominal weight of weld consumable.</td>
</tr>
<tr>
<td>Welds (by points)</td>
<td>13min/point</td>
<td>Minutes to weld in the field, per individual weld line for weld setup.</td>
</tr>
<tr>
<td>Bolting</td>
<td>4.2min/bolt</td>
<td>Minutes to bolt in the field, for each bolt.</td>
</tr>
<tr>
<td>Freight/ Field Costs</td>
<td>$101/tonne</td>
<td>Shipping costs/unloading, plus generalized cost to erect steel on the site, per weight of all components.</td>
</tr>
</tbody>
</table>

### Detailing Preferences

<table>
<thead>
<tr>
<th>Detailing Preferences</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt Size</td>
<td>22mm</td>
<td>Dia of A325 bolts used</td>
</tr>
<tr>
<td>Fillet Leg</td>
<td>8mm</td>
<td>Minimum size for fillet welds</td>
</tr>
<tr>
<td>CJP root dimension</td>
<td>9.5mm</td>
<td>Smallest gap between welded members, affects the volume of weld.</td>
</tr>
<tr>
<td>CJP bevel angle</td>
<td>35°</td>
<td>Sets the angle of single bevel welded member, affects the volume of weld.</td>
</tr>
</tbody>
</table>

*Table A. Fundamental Price Rates and Detailing Preferences*