Integrating Constructability into Conceptual Structural Design and Optimization

by

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B.S. Civil and Environmental Engineering
Cornell University, 2009

Submitted to the Department of Civil and Environmental Engineering in
Partial Fulfillment of the Requirements for the Degree of

Master of Engineering in Civil and Environmental Engineering

at the

Massachusetts Institute of Technology

June 2015

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Abstract

This thesis encourages interdisciplinary design exploration through consideration of constructability in conceptual structural design. Six new metrics are introduced to measure variability in structural components, impose reasonable construction constraints, and encourage standardization of structural characteristics which can improve the ease, efficiency, and costs of construction. This thesis applies these original constructability metrics to truss façade structures for an objective, quantitative comparison with structural performance metrics. The primary contribution of these new metrics is a computational method that can aid in identifying expressive, high-performing structures in the conceptual design phase, when decisions regarding global structural behavior have the greatest impact on multi-objective project goals.

Key words: constructability, conceptual structural design, structural optimization, construction, buildability, structural design tools

Thesis Supervisor: Caitlin T. Mueller
Title: Assistant Professor of Architecture

Acknowledgements

This thesis would not have been possible without the guidance of my advisor, professors, colleagues, and friends. I would first like to thank my thesis advisor, Professor Caitlin Mueller, for her encouragement, support, and wealth of knowledge surrounding structural design and computation. I am extremely grateful for Professor Mueller's enthusiasm and generosity with her time, knowledge, and resources, which allowed for enjoyable and enlightening research.

I would also like to thank my professors within the High Performance Structures program who provided various perspectives and feedback throughout the development of this thesis, specifically Professor John Ochsendorf, Professor Jerome Connor, and Doctor Pierre Ghisbain. I am grateful to have been included in the Structural Design Lab meetings and for the opportunity to receive insightful feedback from numerous colleagues at MIT. Within the Structural Design Lab, I would like to thank Nathan Brown and Stavros Tseranidis for their contributions to my research, including multi-objective visualization techniques and sampling algorithms.

I am thankful for the opportunity to work for two exceptional contractors, Skanska and Clark Construction, prior to my enrollment in the High Performance Structures program. My roles at these companies provided the experience and perspective required to complete this research. I am extremely grateful to my colleagues at Skanska for allowing me to collaborate on a landmark project, the Transbay Transit Center. My time spent on this project proved to be instrumental in the goals set for my research and future design work.

Finally, I would like to thank my parents, Milton and Mary Gayle Horn, for their unwavering support and guidance in my academic pursuits. I am grateful to my parents, as well as my siblings, for providing countless sources of encouragement, advice, motivation, and feedback throughout my academic and professional careers.

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List of Mathematical Symbols

Symbol	Meaning
A_b	Truss element cross-sectional area governed by buckling
A_s	Truss element cross-sectional area governed by axial stress
A_{req}	Truss element required cross-sectional area based on buckling and axial stress
B	Bay width
BC_i	Number of bolted connections for every segment, i
$\boldsymbol{C}$	Node and element connectivity matrix
d_i	Truss element cross-sectional area inside diameter
d_o	Truss element cross-sectional area outside diameter
E	Modulus of elasticity of steel
F	Axial force of a truss element
H	Bay height
I	Moment of inertia of a cross section
L	Element length
l	Spliced segment length
l_{min}	Minimum arc-length required between elements of a single node
$\boldsymbol{M}$	Matrix representing unique set of nodes
$\boldsymbol{N}$	Matrix representing element start and end points
P	Lateral load applied to façade structure
r_i	Cross-sectional area inside diameter
r_o	Cross-sectional area outside diameter
$r_{req,I}$	Radius required to achieve minimum arc-length constructability constraint
$Score_{CSV}$	Cross-section variation constructability metric
$Score_{FC}$	Field connections constructability metric
$Score_{NAC}$	Node angle connectivity constructability metric
$Score_{NMC}$	Node member connectivity constructability metric
$Score_{SL}$	Standardized length constructability metric
$Score_{SW}$	Structural weight performance metric
$Score_{TR}$	Trucking requirements constructability metric
t	Cross-sectional area required thickness
W	Weight of truss element
$W_{segment,i,j}$	Weight of spliced segment
WC_j	Number of welded connections for every segment, j
α_{min}	Minimum angle between elements around a single node
ρ_{steel}	Steel density
$\sigma_{allowable}$	Allowable stress for steel truss elements

CHAPTER 1:
Problem Statement

This thesis presents a new methodology to explore constructability in conceptual structural design. The first chapter outlines commonly accepted definitions of constructability, expands upon this term, and identifies the need for more thorough consideration of constructability in contemporary design processes.

1.1 Motivating Example

Advances in analysis and design software allow designers to explore structures in conceptual design that are increasingly complex and unique. As these geometries move beyond design and into the construction phase, complex connections and flows of forces are often resolved with the use of cast nodes. These components have the ability to yield thousands of different geometries while appealing to the aesthetic quality required by architects (Coenders, 2007). However, the fabrication processes for these components require as much consideration as the complex geometries they resolve, as this lengthy process relies heavily on experienced fabricators, rather than advanced technologies (Coenders, 2007).

Figure 1.1 shows a typical cast node fabrication process before the castings are fit-up for connection plates and welding on site. The Transbay Transit Center project in San Francisco, California utilizes nodes that are cast in a similar manner in order to complete the structural basket column connections at the Ground,

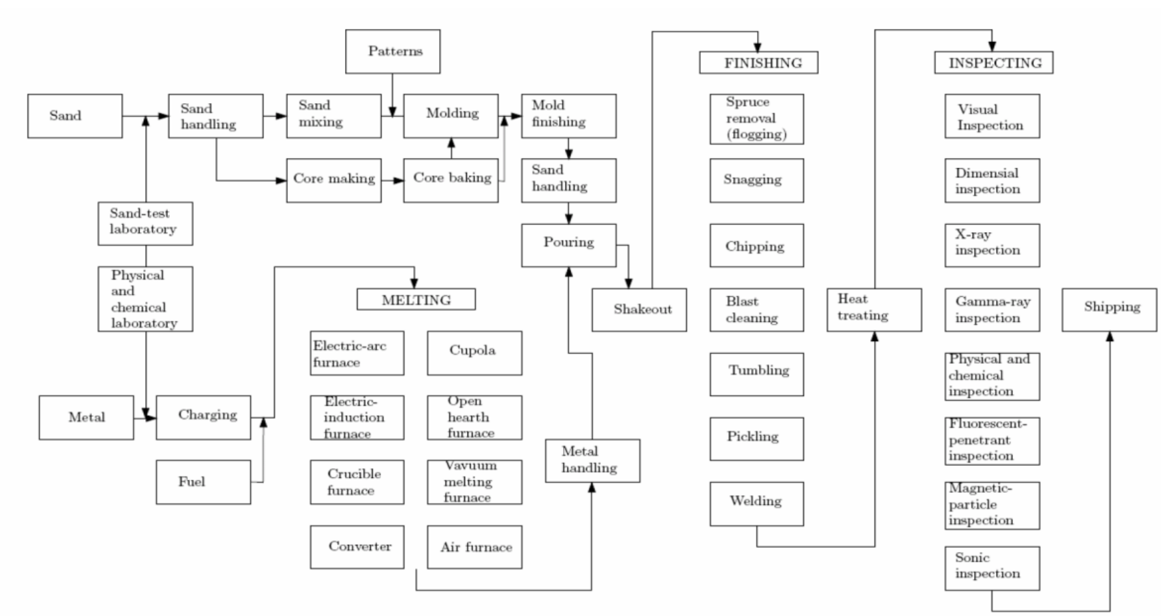
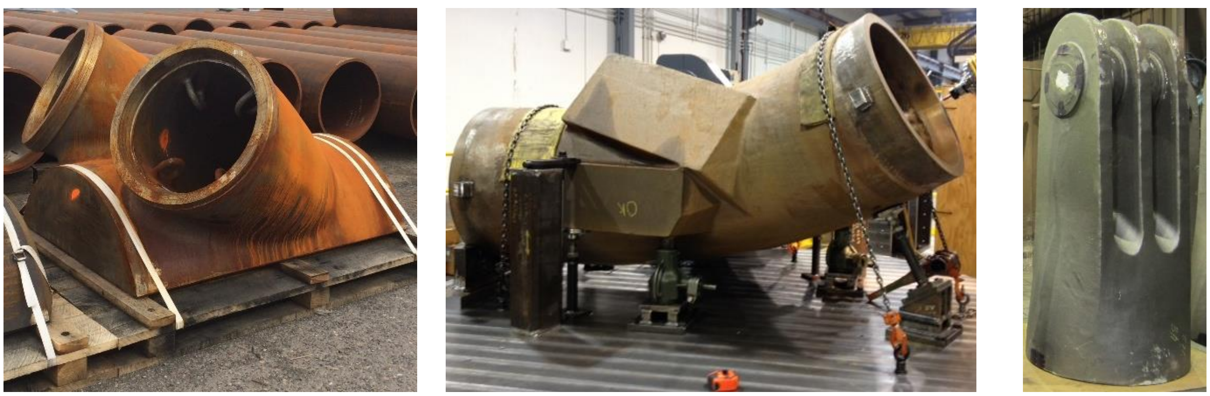


Figure 1.1: *Typical sand casting process in a foundry* (Coenders, 2007).

Bus Deck, and Roof levels. This requires the custom casting of hundreds of nodes, each following the process described in Figure 1.1, in addition to connection plate and trial fit-up at separate fabrication facilities.

Figure 1.2 shows sample castings from the Transbay Transit Center that require months to mold, cast, machine, weld, and fit-up in preparation for arrival on site (Photos by author). An element such as a cast node is a single aspect that can drive a project's cost and schedule due to its geometric and construction complexities. This project exemplifies the concept that early consideration or standardization of complex structural elements can streamline the construction process while decreasing the overall project cost and schedule.



(a) *(b)* *(c)*

Figure 1.2: *Sample cast nodes used for the Transbay Transit center. (a) Ground Level nodes, (b) Bus Deck Level nodes, (c) Roof Level nodes (Photos by author).*

1.2 Need for Constructability in Conceptual Design

Infrastructure development is typically broken down into the following phases: conceptual design, schematic design, design development, and construction (Architects, 2007). Primary structural systems and geometries are often resolved in the first two phases of design while construction experts are unlikely to be involved until the construction phase, after the majority of the design is finalized. The opportunity for construction cost savings are not limited to the construction phase, however, and should be explored during early design phases to reduce overall project costs (Pulaski, 2005).

Figure 1.3 indicates the level of influence the project team has on the cumulative cost of a project over its duration. In the early phases of design, the project team has the most opportunity to impact the cost of the project, while the immediate expenses, such as project fees, are relatively low (Paulson, 1976). The incorporation of construction knowledge becomes difficult during these early design phases, as the level of detail must be tailored to the appropriate phase of the project, necessitating constant interaction with construction and design professionals (Pulaski, 2005).

The exchange of information between construction professionals and designers can become complicated due to contract restrictions and availability of construction knowledge. Most often, the knowledge obtained by construction professionals is not recorded in any form (Pulaski, 2005). To compensate for such difficulties, it is important that design professionals start incorporating basic constructability aspects into conceptual design explorations.

The influence of even the most basic constructability considerations in early design phases can have a significant impact on the overall project cost, duration, and efficiency. For instance, consolidating custom components will expedite fabrication, as fewer unique parts are required and processes can be repeated. This is exemplified in the design of the Basrah Sports City stadium in Basrah Province, Iraq. While the original design called for 10 custom panels to make up the exterior stadium façade, a request to expedite the project schedule called for the consolidation of these custom components to just 5 panels (Tomasetti, 2015). This exercise cut the production in half, exemplifying need for more consideration of constructability aspects in early conceptual design, when important design changes can be executed.

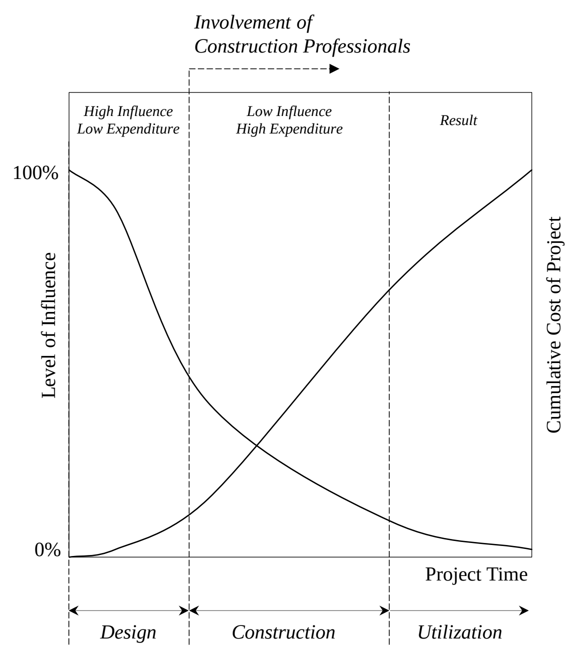


Figure 1.3: *Level of influence of project team on construction cost* (Paulson, 1976).

1.3 Defining Constructability and Trade-offs

Historically, the concept of constructability has been defined as the optimum use of construction knowledge and experience in planning, engineering, procurement, and field operations to achieve overall objectives (O'Connor, 1987). O'Connor focuses on the integration of construction knowledge into various design phases and relies heavily on personnel experts, while constructability measures remain subjective and qualitative.

Another definition of constructability, or "buildability," is the extent to which a project utilizes construction resources available while enhancing safe construction methods and meeting client needs (Lam, 2006). This model attempts to analyze design decisions that are often made beyond the stages of conceptual design. Lam notes the importance of managing constructability criteria in conjunction with client expectations in the early stages of design, prior to the on-boarding or awarding of a project to a construction team (Lam, 2006). This definition of constructability focuses heavily on behavioral adjustments, rather than measurable structural characteristics.

While most methodologies approach constructability from a multi-disciplinary standpoint, some research goes a step further by narrowing in on detailed constructability metrics. Lam's definition of buildability, the term commonly substituted for constructability in the U.K., aligns closely with that of Fischer, whose primary concern is with the design-construction interface. Fischer focuses on structural design aspects that can improve constructability, such as member sizing, distance between elements, modularity, and repetition (Fischer, 1997). While Fischer makes the important realization that the design-construction interface produces trade-offs that are worthy of exploration, this model focuses solely on organization of knowledge and lacks quantitative exploration of such tradeoffs.

Prior research approaches the widely accepted concept that constructability is enhanced when standardization and repetition are utilized, though many definitions of constructability remain behavioral (O'Connor, 1987). For this reason, this thesis will define constructability as the standardization of primary structural elements to balance multi-objective design goals. Further, this thesis will use non-subjective, quantifiable metrics to measure standardization of structural components.

1.4 Quantifying Standardization

A major difficulty with universal applications of constructability is the inability to quantify objectives. Factors impacting constructability are diverse and include project complexity, design practices, project delivery, project size, project type, client type, project location, and design standards (Arditi, 2004). These components are all likely to impact a project at different phases, while many are hard to quantify or unknown at the early stages of design. This thesis attempts define and quantify aspects of constructability which are subject to complexity and stand to benefit from standardization in early project development.

Various attempts have been made to quantify universally accepted constructability objectives. For instance, a multi-variable decision-making model has been developed to quantify the importance of both internal and external project conditions to classify the risk associated with projects (Skibniewski, 1999). Factors such as schedule, cost, materials, equipment, labor, and quality are evaluated through a complex information network to rank the relative importance of various objectives. While this model successfully quantifies relative importance of general objectives, it fails to identify key trade-offs between these objectives. Further, this complex information network, represented in Figure 1.4, does not focus on trade-specific characteristics that can improve constructability.

A model developed by Pulaski and Horman attempts to quantify constructability metrics through organization and comparison matrices (Pulaski, 2005). The model shown in Figure 1.5 is intended to guide the design team on constructability decision making while ensuring that an adequate level of detail is addressed in the appropriate phase. Models such as this attempt to measure effectiveness through feedback and comparison over the duration of the project. It can be seen, however, that this methodology quickly becomes cumbersome and is only effective when meaningful knowledge is presented and a baseline for comparison is available.

Another common method for quantifying and analyzing constructability is through the use of surveys. One survey attempts to quantify the effectiveness of standardization and repetition by asking designers to rank the attribution of such factors to the ease of construction on completed projects (Lam, 2006). Other contributing factors include coordinated drawings and specifications, safe sequencing of work, and coordination between trades. This quantification focuses mainly on the construction phase rather than the early design phases. Further, the information obtained from this survey yields behavioral modifications to be made throughout the design process, rather than objective, quantifiable metrics.

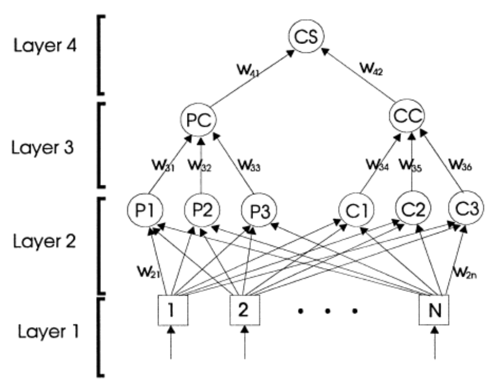


Figure 1.4: *Multi-layer information network proposed for constructability evaluation* (Skibniewski, 1999).

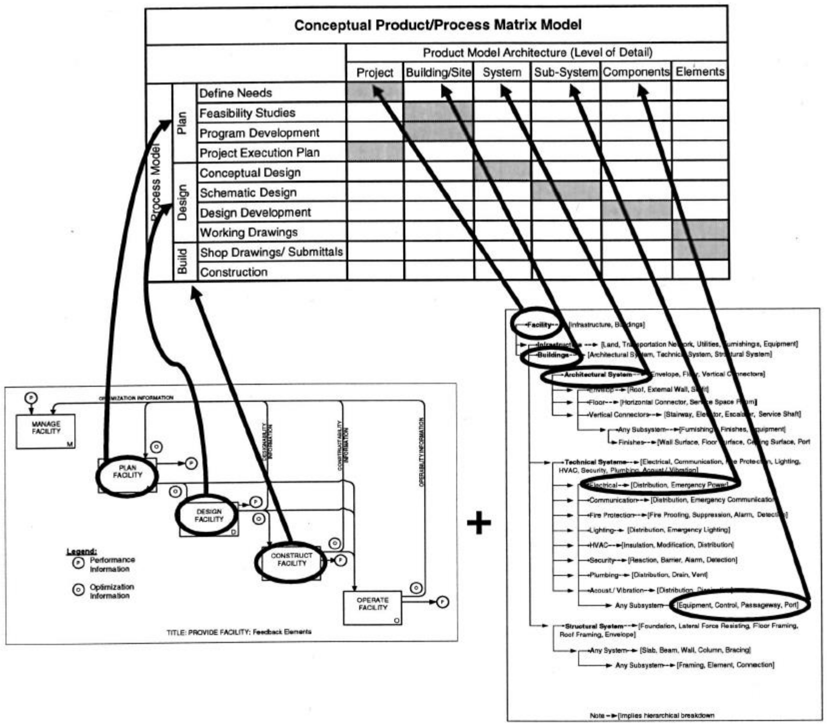


Figure 1.5: *Conceptual product/process matrix model used to encourage constructability in all phases of project development* (Pulaski, 2005).

Arditi attempts to quantify the design teams' behaviors in regards to incorporation of constructability through surveys. Such an approach yields statistics on designers' tendencies to consider constructability throughout various phases of design. Figure 1.6 shows a summary of this behavior, indicating that a mere twenty-five percent of designers perform constructability analysis throughout the entire design process, while the majority of design professionals consider this to be an important objective (Arditi, 2004). This shows that while architectural and structural design firms are showing a growing interest in the integration of constructability into the early stages of design, few have developed standardized methods for performing constructability reviews.

As computational design tools expand, engineers and designers are creating more advanced methods for measuring complex variables. For instance, Zhu's research develops an optimization algorithm for optimization of the discrete variables often encountered in structural design, such as cross section sizes (Zhu, 2014). This research, however, lacks the application of such algorithms to rigorous constructability metrics.

The research presented above shows that approaching the issue of constructability from a multi-disciplinary standpoint can lead to generalized, behavioral solutions. It is also shown that the structural design industry has a rapidly growing interest in improving constructability, while the tools to do so are primarily based on designer behaviors. This thesis quantifies constructability characteristics objectively through multi-objective optimization and explores key metrics that can improve performance along the construction-design interface. While quantification of the constructability process started its development in the 1980s, little research has addressed the quantification of objective constructability metrics via standardization in conceptual design.

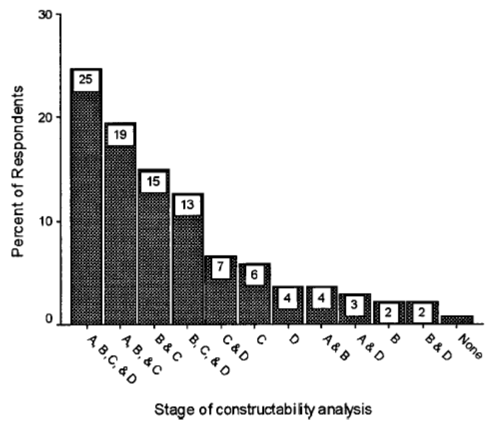


Figure 1.6: *Timing of constructability reviews: (A) concept design, (B) schematic design, (C) detailed design, (D) procurement and execution* (Arditi, 2004).

This thesis develops original metrics for the precise analysis of constructability based on structural characteristics that can be explored in conceptual design. By implementing a quantifiable, multi-objective exploration, design solutions can aid in early project decision making, often before construction professionals can be on-boarded in project development.

1.5 New Contributions

This thesis provides two original contributions to the integration of two important objectives in conceptual design: constructability and structural performance. The first new contribution is the development of a set of standardization metrics applied to steel cast node structures. The second original contribution explores the application of these metrics in a multi-objective design example of a two-dimensional steel truss façade structure. These contributions are an important first step in quantifying multi-objective performance to decipher qualitative characteristics in high-performing designs.

This chapter has introduced definitions of constructability and identifies the need for quantifiable objectives to aid in conceptual structural design explorations.

Chapter 2 introduces new constructability metrics based on fundamental structural and geometric characteristics such as element sizing, element lengths, and node connectivity. These original constructability metrics are applied to a parametric framework to promote ease of construction through standardization of structural components.

Chapter 3 evaluates the data collected from the new constructability metrics and compares these results with structural performance. Standardization is imposed on structural elements to identify tradeoffs between two design objectives. Structural elements characterizing both high and low performing designs are identified.

Chapter 4 summarizes the results of the multi-objective optimization process and discusses the potential impact of these contributions in conceptual structural design.

CHAPTER 2:

Constructability Analysis

In the design of discretized structures, such as trusses, standardization of structural elements such as member length, member size, and node connectivity, can enhance fabrication and labor in the project implementation phase. This chapter introduces new constructability metrics that encourage the standardization of key structural elements to enhance overall structural performance in conceptual design.

2.1 Problem Mechanics

This section introduces the method used for exploring the multi-variable design space through topological and geometric randomization. This study focuses on two-dimensional steel truss façade structures subject to lateral loading with a pinned base.

2.1.1 Model Overview

Figure 2.1 provides an overview of the two-dimensional steel truss façade design variables, including node translation in the horizontal and vertical directions and diagonal members subject to topology variations. This model is generated using Rhinoceros 3D (Rhino) software with the Grasshopper 3D plugin, a parametric design framework (Robert McNeel & Associates, 2014). Structural analysis is performed primarily with Karamba, parametric engineering software that is compatible with Grasshopper (Preisinger, 2015). The goal within this parametric framework is to explore unexpected and interesting structural solutions that are still high-performing in the proposed multi-objective space.

In this model, geometric randomization is carried out through varying the vertical and horizontal positions of nodes, or points at which members frame into a single point. Nodes subject to position variation in the horizontal direction and are constrained to fifty percent of the original bay width, *B*. Nodes subject to position variation in the vertical direction are constrained to forty percent of the original bay height, *H (see Figure 2.1)*. The number of vertical bays is also a variable, and this study explores façade systems with five or six vertical bays.

Topological randomization is completed via Boolean operators that turn diagonal elements on or off. Each quadrant in the original model contains four diagonal elements, where each diagonal element has a forty percent chance of removal during each design iteration. Once elements are randomly removed, a stability check is performed on the structure and unstable elements (those with one or less connecting elements) are removed to eliminate local instability. Symmetry is induced about the vertical axis of the façade.

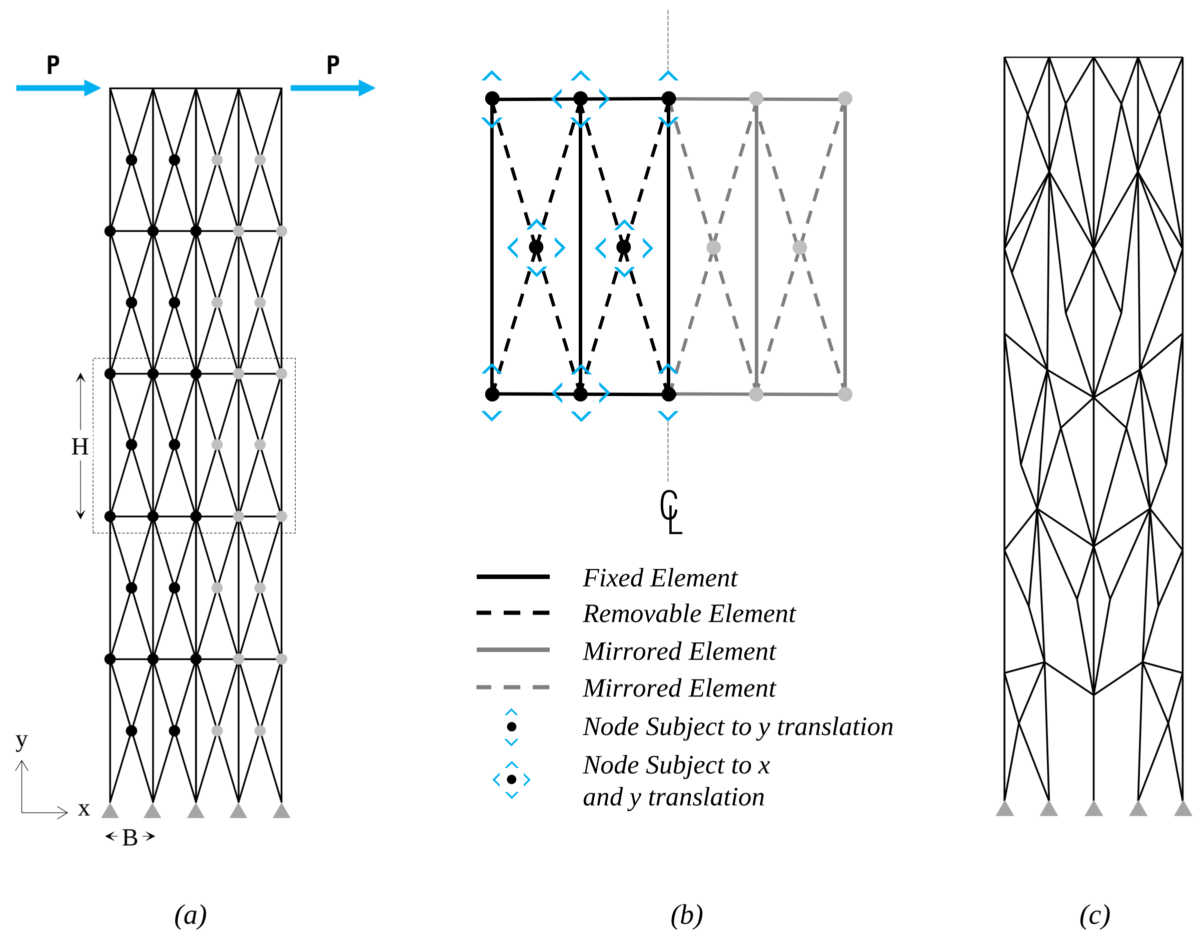


Figure 2.1: *Two-dimensional façade structure subject to geometric and topological variations. The variables shown in this model are randomized to explore the design and objective spaces. (a) Initial structure before modifications are imposed. (b) Variable settings including node translations and members subject to topological modifications. (c) Sample output designs based on variable randomization.*

2.1.2 Structural Analysis

Once the model framework is constructed, it is imported into Karamba for analysis. This structural analysis tool is set up such that every point along the base of the structure is pinned (zero translation in the x and y directions). All points are pinned in the z-direction to prevent out of plane movement. A Boolean operator is used to turn bending in all elements 'off,' creating only truss elements with axial forces. Two point loads of 500 kips are applied in the positive x-direction at the top of the structure. The fixities and loads are graphically represented in Figure 2.1.

In the initial structural analysis, Karamba's *Optimize Cross Section* tool is used to preliminarily size elements and determine the initial distribution of forces. The *Optimize Cross Section* tool is allowed to select any circular cross section available within the built-in Karamba library to meet stress and buckling demands. Once the cross sections are selected and the structural analysis is completed, the primary structural performance criteria can be extracted from Karamba tools, including lateral deflection and strain energy. However, more control over the member sizing is required for manipulation and evaluation of constructability metrics; therefore, the structural weight metric is based on the member sizing calculations discussed in detail in Section 2.1.3. The structural performance metrics are explained in further detail in Section 2.2.

2.1.3 Member Sizing

While Karamba is used to determine the distribution of forces in the façade structure, a separate sizing algorithm is used in this study to generate steel hollow tube member sizing. This allows for a more diverse exploration of member size standardization as described in Section 2.4. Member sizing is determined based on the minimum area required to satisfy both stress and buckling criteria. The maximum compressive and tensile forces in the structure are extracted for each member and these maximum forces are checked against their mirrored counterpart to ensure the structure is suitable for loads in positive and negative x-directions.

$$A_s = \frac{F}{\sigma_{allowable}} \qquad \textit{(Eq. 2.1)}$$

$$t = r_o - r_i = 0.05(2 \cdot r_o) \qquad \textit{(Eq. 2.2)}$$

$$r_o = \sqrt{\frac{A_s}{\pi(1-.9^2)}} \qquad \textit{(Eq. 2.3)}$$

Equations 2.1 through 2.3 identify method for determining the required cross sectional area for stress calculations, where F is the maximum axial force, $\sigma_{allowable}$, is taken to be 36 kips per square inch, t is the pipe thickness, and r_o and r_i are the pipe outside and inside radii, respectively. The thickness of each section is initially assumed to be 5 percent of the outer diameter. This methods yields a final outside diameter and thickness for each pipe member in the structure. This information is then used to ensure that all members satisfy buckling requirements.

The buckling check starts with the assumption that the member thickness is the same as that obtained from the stress calculations. This simplifies the buckling calculation and ensures that any upsize in the pipe diameter will maintain a cross sectional area that satisfies both the required cross sectional area for stress, A_s, and that required for buckling, A_b. Equations 2.4 through 2.6 walk through the calculations used to obtain the required cross sectional dimensions to satisfy buckling with a safety factor of 3.

$$I = \frac{\pi(d_o^4 - d_i^4)}{64} \qquad \textit{(Eq. 2.4)}$$

$$F = \frac{n\pi^2 EI}{3L^2}, n = 1 \qquad \textit{(Eq. 2.5)}$$

$$d_o = \left[\frac{3 \cdot 64 L^2 F}{\pi^4 E(1-.9^4)}\right]^{\frac{1}{4}} \qquad \textit{(Eq. 2.6)}$$

Once the required outside diameter, d_o, is calculated and the required thickness, *t*, is known, the final cross sectional area, A_{req}, is determined by choosing the maximum between A_s and A_b. To simplify fabrication and build-in basic standardization constraints, the thickness associated with the required area is rounded up to the nearest eighth of an inch and the required diameter is rounded up to the nearest inch. The resulting diameter and thickness, $d_{0,req}$ and t_{req}, are recorded based on the chosen area, A_{req}. The resulting values from these member sizing calculations are used to evaluate several metrics discussed in Sections 2.2.3, *Structural Weight*, and 2.3, which introduces several new constructability metrics.

$$A_{req} = \max\{A_s, A_b\} \qquad \textit{(Eq. 2.7)}$$

2.1.4 Design Space Sampling

Once the model framework, structural analysis, and sizing are set up in the parametric design space, the objective space is sampled through Latin hypercube sampling of the design variables (Tseranidis, 2015). Objectives, or constructability and structural performance metrics, are later defined in Sections 2.2 and 2.3. Latin hypercube sampling is used to ensure each design variable is randomly sampled at a rate proportional to its distribution for accurate evaluation of the design space (McKay, 1979).

2.2 Structural Performance Metrics

Structural performance is evaluated using the structural analysis software, Karamba, as outlined in Section 2.1.2. The following briefly describes the metrics that quantify structural performance, which are later compared with constructability performance metrics defined in Section 2.3.

2.2.1 Lateral Deflection

The Karamba *Analyze* tool is used to determine the overall lateral deflection of the façade system at the top of the structure. The output of this tool is used as the *Lateral Deflection* score and is based on the cross sections generated via the *Cross Section Optimize* tool, rather than the sizing calculations described in Section 2.1.3. This measure remains valid, however, as the force distribution of materials remains comparable for all analyses. Further, the sizing described in Section 2.1.3 is proportional to the sizing and weights generated from the *Cross Section Optimize Tool,* though the thickness and diameter proportions may vary slightly. A penalty score is imposed for invalid designs, or those which are globally unstable, to ensure that no null data is received.

2.2.2 Strain Energy

Strain energy is calculated in kip-feet and is determined by the Karamba *Analyze* tool. Similar to *Deflection* performance, this metric is based on the cross sections and deflections generated using the built-in *Cross Section Optimize* tool in Karamba. A penalty score is imposed for unstable designs to eliminate null scores.

2.2.3 Structural Weight

The *Structural Weight* metric is determined based on the sizing calculations presented in Section 2.1.3. Using the total number of elements, n, cross sectional area for each member, A_{req}, member length, l, and steel density, ρ_{steel}, the overall weight of the structure is calculated using Equation 2.8. Steel density is taken to be 500 pounds per cubic foot. The total structure weight is the final objective for this metric, where a penalty score is imposed for invalid designs to eliminate null scores.

$$W = \sum_{i=1}^{n} A_{req,i} \cdot l_i \cdot \rho_{steel} \qquad \textit{(Eq. 2.8)}$$

2.3 Introducing New Constructability Metrics

With the information obtained from the structural analysis and sizing calculations, new constructability metrics are formulated to measure design characteristics from a constructability perspective. These new metrics vary based on the randomization of design geometry, topology modifications, and force distribution. The following describes each of the new constructability metrics, which are based on the assumption that constructability improves with the implementation of standardization for key structural components.

2.3.1 Metric 1: Standardized Member Length (SL)

The standardization of member length is the first metric considered. This method calculates the average member length for each design iteration. Once the mean member length is calculated, each member is penalized based on its difference from the mean. Figure 2.2 shows a sample distribution of member lengths, where the standard member length score for the total structure, $Score_{SL}$, is the summation of all differences from the mean member length. The objective is to minimize the total score, $Score_{SL}$, resulting in less overall variation in member lengths across the structure.

This method outlines a very basic objective; however, this particular approach may not encourage an ideal outcome from the standpoint of constructability enhancement. By minimizing this objective, the member sizes approach the mean value, but are unlikely to match it. This results in components that are close to the mean value, but have slight variations in length. A more practical application of standardizing member length may be to consolidate members into sets of standard lengths that fit certain characteristics of the population distribution shown in Figure 2.2. By consolidating member lengths based on quartile ranges, for example, the fabrication and erection procedures are likely to improve. (See Chapter 4, Section 4.3 for future implementation and recommendations).

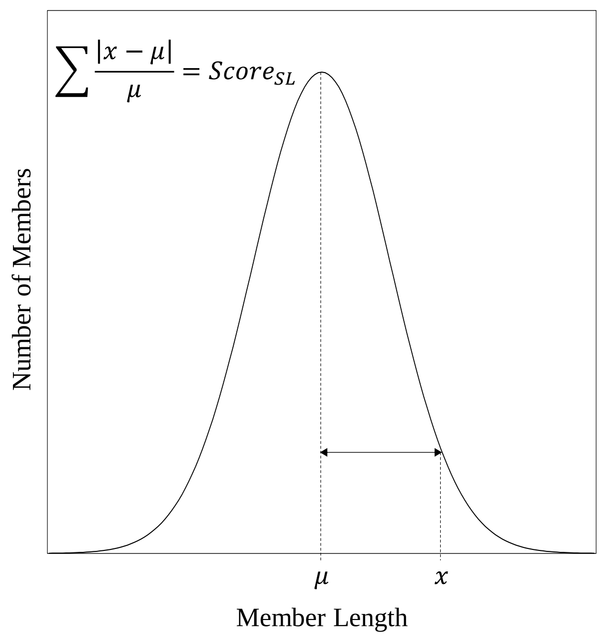


Figure 2.2*: Sample distribution of member lengths and calculation of standard member length scores.*

2.3.2 Metric 2: Trucking Requirements (TR)

An improved metric in regards to individual member characteristics integrates member length, member weight, and shipping constraints. An important contribution to ease of construction is the shipping requirements for structural elements. In the United States, special permits are typically required for "oversized loads," where the criteria for the term "oversized" is determined on a state-by-state basis. In the state of Massachusetts, for example, Special Hauling Permits are required for any loads that exceed 49.5 tons or 80 feet in length (for ease of construction, the use of an escort is considered to negatively impact constructability and is therefore included in the constraint) (Massachusetts, 2015).

This metric utilizes the constraints imposed by the Massachusetts Department of Transportation and imposes the length and weight restrictions for Special Hauling Permits on the structural elements. Using element lengths and cross sectional areas, components are broken down to determine an approximate value for number of trucks required to deliver all structural elements to the site. The process for calculating this metric is depicted in Figure 2.3 and is detailed as follows.

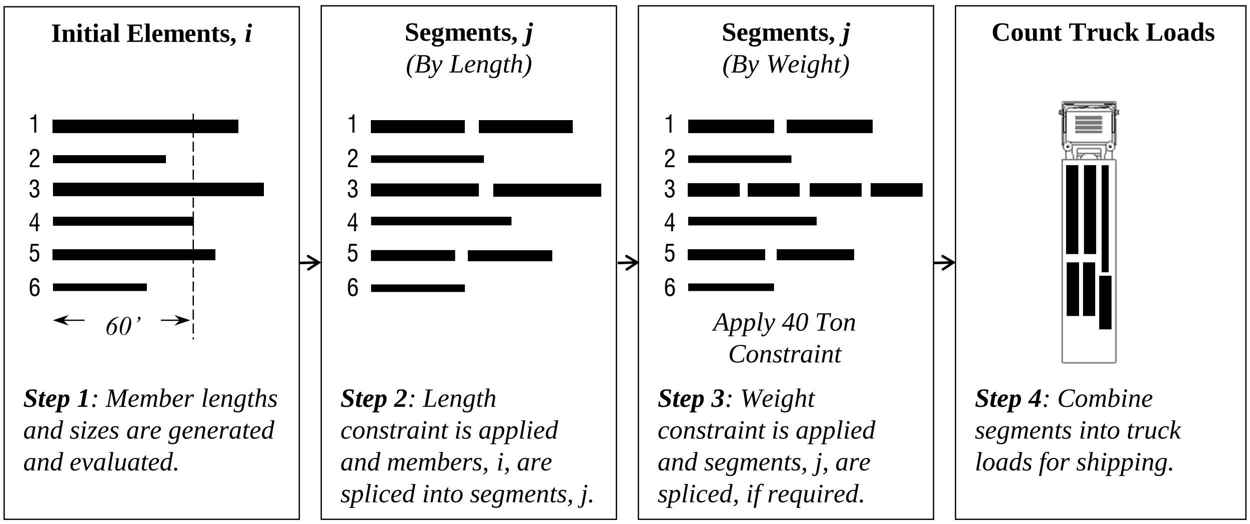


Figure 2.3: *Process for evaluating member sizing and generating truck loads required to formulate the Trucking Requirement score, Score$_{TR}$.*

First, the constraint on shipping length is imposed. The tractor-trailer assembly can be no longer than 80 total feet; therefore, after consideration of the length of the tractor, each member length is constrained to be no longer than 60 feet. Members longer than 60 feet are cut into as many equal segments as are necessary so that all spliced segments, or those that are cut for shipping and later connected on site, are less than 60 feet. The cross sectional area of each segment is used to calculate the weight of that segment based on its new length. If the weight of the segmented element exceeds 40 tons, allowing for the weight of the truck and rigging, the element is then spliced a final time until the required constraint is reached. The mathematical implementation of these constraints is expressed in Equations 2.9 through 2.11 and graphically in Figure 2.4.

The method described thus far is an initial pass to ensure that the basic shipping constraints are satisfied by each segment, j. The next step is to consolidate members into shipments that do not exceed the oversized shipping restrictions. Starting from the base of the structure and working towards the higher elevations. Knowing that each individual segment now satisfies the length constraint, and assuming segments can be stacked, the weight of consecutive segments, or spliced elements, is added until the constraint of 40 tons is reached. At this point, one truckload is counted and the weight resets to zero tons. This process is repeated until another truckload is filled and counted and all members have been "shipped."

The assumption that segments can be stacked is based on the premise that the weight constraint will always govern, rather than the truck's volume constraint. Considering a shipment where the average member size is 1 foot in diameter, a half inch thick, and 40 feet long, the weight constraint is reached after less than two stacked rows are completed (considering a truck bed that is 10 feet wide). At this point, the volume of the truck is utilized to less than 50 percent, while the weight constraint is exceeded. Therefore, this is taken to be a valid assumption within the *Trucking Requirements* metric.

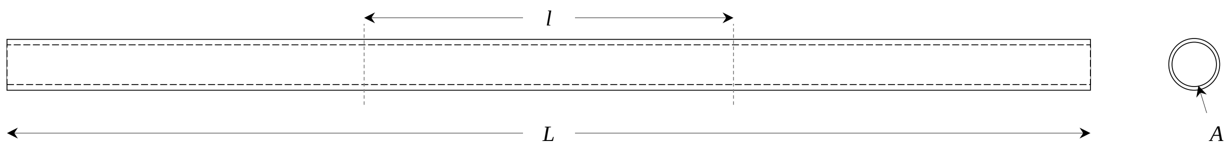


Figure 2.4: *Shipping length and weight constraints are applied to individual structural elements to estimate project shipping requirements. Further, spliced segments are combined onto trucks, which are counted to formulate the final shipping criteria score, Score$_{TR}$.*

$$l_i = \frac{L}{\texttt{ceiling}\,(L/60ft)} \qquad \text{(Eq. 2.9)}$$

$$W_i = A_i l_i \rho \qquad \text{(Eq. 2.10)}$$

$$w_{segment,i,j} = \frac{W_i}{\texttt{ceiling}\,(W_i/40tons)} \qquad \text{(Eq. 2.11)}$$

The final objective of the shipping criteria function, *Score$_{TR}$*, is to minimize the total number of required truck loads. The objective function used to evaluate the trucking requirement scoring is indicated in Equation 2.12. By minimizing or eliminating the need for oversized shipments, constructability is improved as there are significant time constraints and site logistics associated with trucking and oversized load permitting. With standard shipping, the timing of shipments can be better coordinated with on-site work, yielding construction cost savings.

$$Score_{TR} = \texttt{ceiling}\left(\frac{\sum_{j=1}^{n} w_{segment,i,j}}{40\ tons}\right), for\ each\ member, i, and\ segment, j \qquad \text{(Eq. 2.12)}$$

2.3.3 Metric 3: Field Connections

As a result of the trucking restrictions and member splicing explored in Section 2.3.2, segmented structural elements must be connected and assembled on site. The number of field connections, bolted and welded, will vary depending on the number of segments required for shipping and the total number of members in the structure. In general, minimizing the total number of field connections will reduce the number of man hours expended on site for laborers and crane operators. In the evaluation of field connections, it is proposed that a reduction in the number of field connections will increase constructability.

The field connections metric can be expanded from the trucking requirements metric. Based on the number of splices required to satisfy the trucking constraints, the total number of bolted and welded connections can be measured. In this study, which considers only truss elements, it is assumed that all members are pinned connections and can be bolted at the nodes and are fully welded at intermediate member splices. This concept is depicted in Figure 2.5, where the term BC_i indicates a bolted connection and WC_j indicates a fully welded connection for each member, *i*, in the structure. Note that members can be fully welded at the nodes; however, this research considers bolted connections to depict quantification of varying connection types.

Taking into account member splicing, the field connection metric is summed as indicated in Equation 2.13. In this objective function, *b* indicates the total number of bolted connections and *w* indicates the total number of welded connections. Also shown in this objective function are two optional coefficients, A and B, which can be used to weight field bolted and field welded connections, respectively. For example, depending on means and methods, welded connections can be weighted to be twice as difficult as field connections by using $B=2$ and $A=1$. In this study, it is assumed that bolted and welded connections have the same level of complexity, therefore both values are set to one.

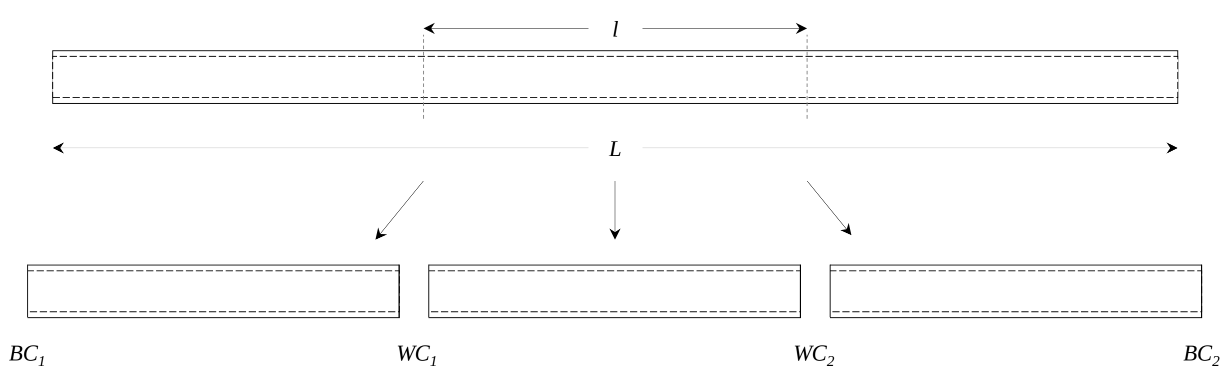


Figure 2.5: *Field connections are broken down into* BC*, bolted connections and* WC*, welded connections. These scores are counted, weighted, and summed to generate the Field Connections metric,* $Scores_{FC}$*. See Eq. 2.13.*

$$Score_{FC} = A \cdot \sum_{i=1}^{b} BC_i + B \cdot \sum_{j=1}^{w} WC_j \qquad \text{(Eq. 2.13)}$$

The overall goal for the field connections metric is to minimize the objective function indicated in Equation 2.13. By minimizing this objective function, high performing structures will have the least amount of field connections which will reduce project labor hours and on-site logistical complexity.

2.3.4 Metric 4: Node Member Connectivity (NMC)

Node connectivity can impact cast node geometry and fabrication processes, such as the one detailed in Section 1.1. The complexity of these cast node components can great greatly impact a structure's overall constructability. For this reason, the node connectivity is measured in an attempt to maximize the accessibility of the laborers to the cast node pads and minimize the number of infeasible connections. Two metrics are used to measure node connectivity.

A first step to measuring the node connectivity is to minimize the number of members framing into a single node. This metric is evaluated by first considering a structure with i elements. Each element has a start node and an end node at the coordinate (x_i, y_i). These nodes are stored in a matrix with dimensions $n \times 2$, where n is the number of start node points and the two columns correspond to the x and y coordinates of each point. Element end node points are assembled into a similar $n \times 2$ matrix, where n is also the number of end points and the columns correspond to the x and y coordinates of each point.

These two matrices are joined into a single matrix, $\boldsymbol{N}$, which represents all start and end points with dimensions $2n \times 2$. The set of all unique points in the structure can then be extracted from the node matrix, $\boldsymbol{N}$, and stored in a single matrix, $\boldsymbol{M}$, with the dimensions $m \times 2$, where m is the total number of nodes on the structure and the two columns correspond to the x and y coordinates of each node. Using the set of nodes in matrix $\boldsymbol{M}$, each node in matrix $\boldsymbol{N}$ can be indexed and the number of times each node is indexed can be counted. The number of times each node is counted, j, can be recorded as the number of elements framing into node (x_i, y_i). A graphically and computational representation of node connectivity is shown in Figure 2.6.

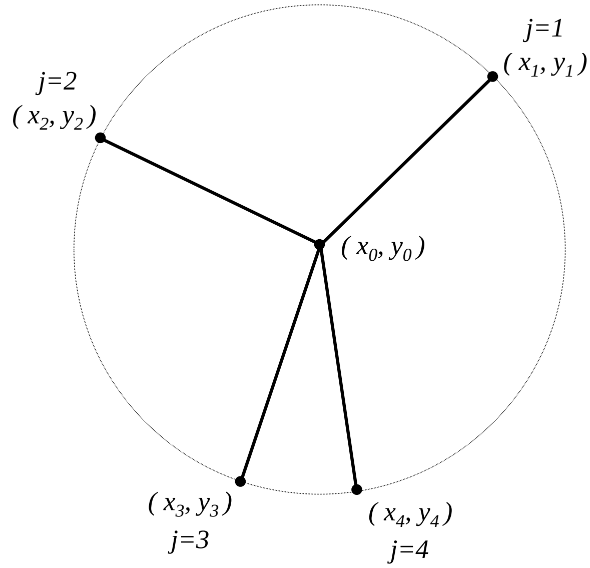
Once the member connectivity is established, the data must be consolidated into a single objective function. A weighted objective function is used for scoring member connectivity based on the rationalization that an increase in members in a single node increases complexity and decreases constructability. Further, the use of too few members in connections is impractical or inefficient. The weighting proposed in Equation 2.14 is arbitrarily based on this logic, but can be adjusted by the user on a case-by-case basis.

The weighted objective function, graphically represented in Figure 2.7, includes the value n_j, where n is the number of times a node with j elements connecting to it occurs. In this metric, the goal is to minimize the weighted objective function indicated in Equation 2.14. As such, this weighting scheme implies that a node with three or four members framing into it is ideal, with decreasing feasibility as more members are added. Additionally, the inefficiency of two member framing into each other is captured with a higher score given to those with two members per node.

$$\boldsymbol{N} = \begin{bmatrix} x_0 & y_0 \\ x_1 & y_1 \\ x_0 & y_0 \\ x_2 & y_2 \\ x_0 & y_0 \\ x_3 & y_3 \\ x_0 & y_0 \\ x_4 & y_4 \\ & \vdots & \end{bmatrix}$$

$$\boldsymbol{M} = \begin{bmatrix} x_0 & y_0 \\ x_1 & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \\ x_4 & y_0 \\ & \vdots & \end{bmatrix}$$

(a)



(b)

Figure 2.6*: (a) Matrix representation of elements start and end points matrix,* ***N****, and set of unique nodes,* ***M.*** *(b) Graphical representation of node member connectivity for indexing element start and end points and calculating the number of elements, j, framing into a single node.*

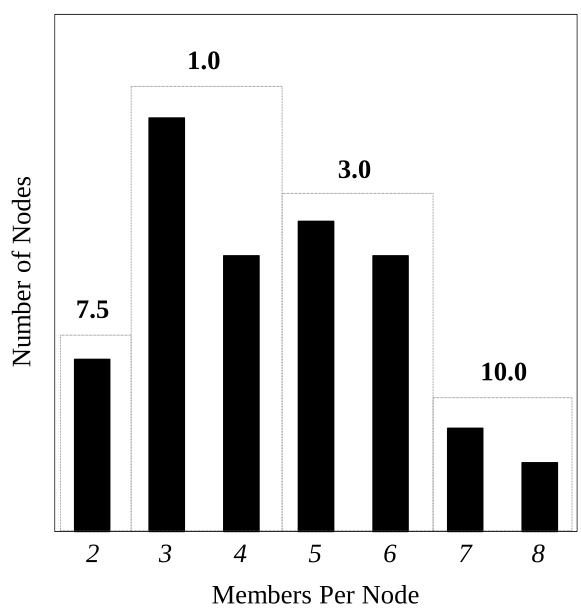


Figure 2.7: *Sample distribution of node connectivity in a structure showing how each node with j number of elements is scored. The value n_j indicates the number of times a node with j elements connecting to it occurs.*

Reducing the number of elements framing into a single node can improve the speed of construction by reducing connection time. Less time in fabrication and erection will be spent at a single point, leading to quicker erection time of the primary structure, allowing for follow on trades and miscellaneous metals to have quicker access to the site.

$$Score_{NMC} = \sum 7.5 \cdot n_2 + 1.0 \cdot n_{3,4} + 3.0 \cdot n_{5,6} + 10.0 \cdot n_{7,8} \qquad \textit{(Eq. 2.14)}$$

2.3.5 Metric 5: Node Angle Connectivity (NAC)

The *Node Angle Connectivity* metric also quantifies the complexity of node angles via implementation of a feasibility constraint. In order for cast nodes to be feasible, each member framing into the node must have a minimum separation, indicated by the arc length, l_{min}, shown in Figure 2.8. This minimum clearance ensures that members framing into a node do not clash, and that there is minimum clearance for welding or bolting access. This minimum arc length feasibility constraint, l_{min}, is taken to be eighteen inches and every node is evaluated based on this criterion. In order to score the nodes based on this condition, the parameters indicated in Figure 2.8 must be collected, organized, calculated, and evaluated.

Identical to the node connectivity score outlined in Section 2.3.4, the ***N*** and ***M*** matrices are constructed. From these matrices, a connectivity matrix is created, which defines the connection of structural elements

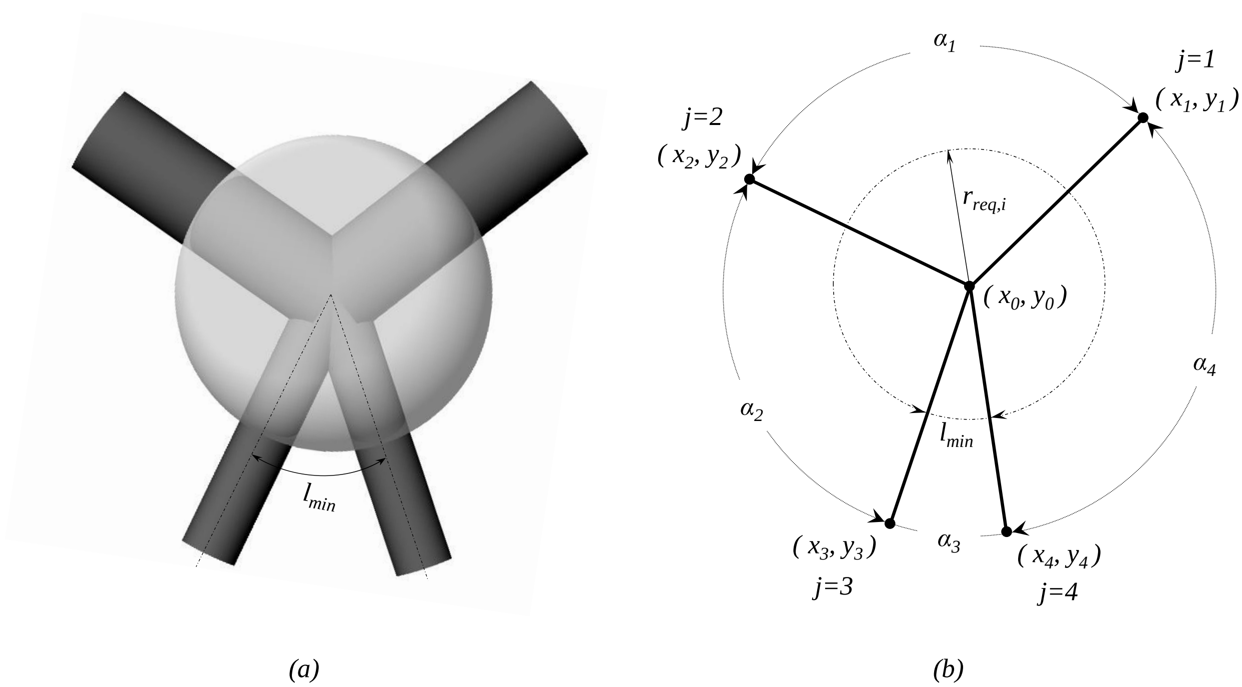


Figure 2.8*: Node angle connectivity parameters and imposed constraints. (a) Modeled representation of a four-member spherical node with imposed constraint, l_{min}. (b) Geometric parameters used to calculate the Node Angle Connectivity metric.*

to each node. The connectivity matrix, ***C***, has dimensions *n x m*, where each row indicates the element number and each column represents a node from the structure. The ***C*** matrix values are made up of three values: 0, 1, and -1. For each row, representing an element, 1 is input in the column representing that element's start point, -1 for the end point, and 0 for all other columns.

Once these matrices are constructed, the points associated with each node are recalculated so that the start point, (x_0, y_0), is the origin *(0, 0)*. Equation 2.15 is used to calculate the new end points (x_i, y_i). With the new coordinate system, the angle between each member, α_j, connecting into a single node is calculated and stored in an angle matrix, *A*. Using the eighteen inch minimum arc length constraint, l_{min}, the radius required to satisfy this constraint can be calculated using Equation 2.16. The minimum arc length is divided by the minimum angle, α_{min}, to find $r_{req,i}$, the radius required by each node to satisfy the arc length constraint.

$$(x_i, y_i) = [\boldsymbol{C}][\boldsymbol{M}] \quad \textit{(Eq. 2.15)}$$

$$r_{req,i} = \frac{l_{min}}{\alpha_{min}} \quad \textit{(Eq. 2.16)}$$

The final objective function is the summation of all radii required to achieve the minimum arc length constraint. Equation 2.17 indicates the final objective function, $Score_{NAC}$. The goal is to minimize this objective function so that the optimum structures have the most spacing between members, or greatest ease of construction. Structures with extremely small angles will score worse, thus high performing structures have more accessibility to make connections, which will improve the ease with which they are fabricated, fit-up, and connected to members.

$$Score_{NAC} = \sum_{i=1}^{n} r_{req,i} \quad \textit{(Eq. 2.17)}$$

2.3.6 Metric 6: Cross Section Variation (CSV)

Variation in cross sectional areas can lead to more complex fabrication and erection processes, particularly in the case of non-standard shapes. In this metric, it is considered that less variation in member sizing will lead to enhanced constructability, therefore high performing structures will have the least amount of different cross sectional areas. The following describes how this is measured.

Consider, based on the member sizing method described in Section 2.1.3, that each structural element has a cross section assigned to it. Each cross section is assigned a numerical value to determine the set of unique cross sections. This numerical value is determined by multiplying the required diameter, in inches, by ten and adding the member thickness in decimal inches. For instance, a member with a 10 inch outside diameter and 1.25 inch thickness would be assigned the numerical value, 101.25, as determined by Equation 2.18.

$$Size = 10 \cdot OD + t \qquad (Eq.\ 2.18)$$
$$OD = Outside\ Dia.\ (in)$$
$$t = thickness\ (in)$$

Based on this set of values, the set of unique cross sections can be counted. The final metric is determined based on the percentage of all members that have unique cross sections. The variation of cross sections score, $Score_{CSV}$, is the number of unique cross sections divided by the total number of elements, as indicated in Equation 2.19. By minimizing this score, this objective function outputs high performing structures as those with more standardization in cross sectional areas.

$$Score_{CSV} = \frac{set\{Size\}}{No.of\ Elements} \cdot 100 \qquad (Eq.\ 2.19)$$

2.4 Implementing Standardization of Member Sizing

In this section, the method of implementing standardization is explored (verses strictly comparing performance). As previously outlined in Sections 2.1.3 and 2.2.5, each design is evaluated and member sizing is selected based on stress and buckling requirements. The metric defined in Section 2.3.6 evaluates individual performance by measuring the range of cross sectional areas selected. However, this exploration goes one step further by resizing members in order to increase standardization of cross sectional areas.

Figure 2.9 shows the process used to consolidate member sizing. The *Original Set* is the set of cross sectional areas determined via stress and buckling analysis and further scored with the Cross Section

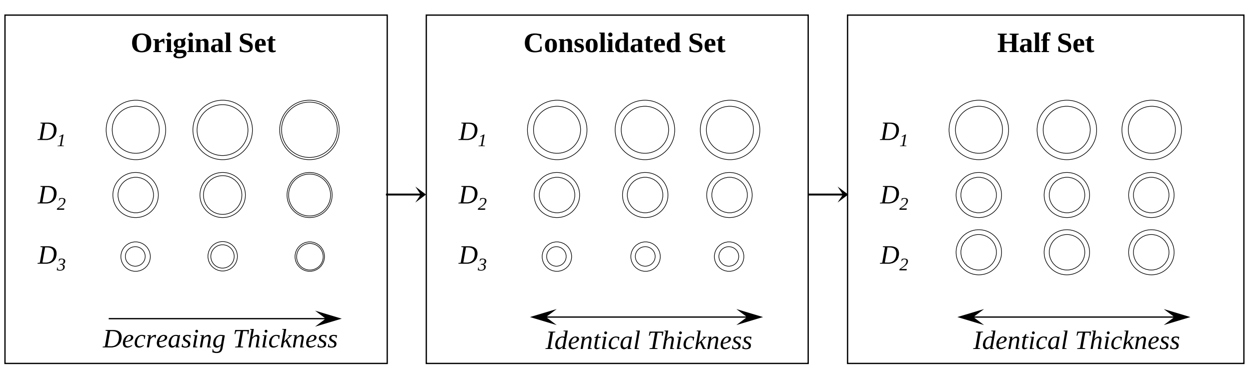


Figure 2.9: *Steps for standardizing cross sectional areas into sets.*

Variation metric, $Score_{CSV}$. Once the original cross sections are determined, all members are broken into sub-sets, each made up of members with the same outside diameters, regardless of thickness. The first step is to consolidate member sizing so that all thickness under each sub-set are upsized to the same thickness. In the *Consolidated Set* shown in Figure 2.9, members in each sub-set, i.e. same outside diameters, have been upsized to identical thicknesses.

Figure 2.9 shows the process used to consolidate member sizing. The *Original Set* is the set of cross sectional areas determined via stress and buckling analysis and further scored with the Cross Section Variation metric, $Score_{CSV}$. Once the original cross sections are determined, all members are broken into sub-sets, each made up of members with the same outside diameters, regardless of thickness. The first step is to consolidate member sizing so that all thickness under each sub-set are upsized to the same thickness. In the *Consolidated Set* shown in Figure 2.9, members in each sub-set, i.e. same outside diameters, have been upsized to identical thicknesses.

Once the consolidated set has been created, with sub-sets including each unique set of outside diameters of equal thickness, the sets can be consolidated further. As indicated in Figure 2.9, in the *Half Set,* every other diameter is upsized to the next largest outside diameter. To ensure that all members still satisfy the stress and buckling requirements, the largest member thickness of the two sets is chosen. This method is then repeated to generate a *Quarter Set*, *Eighth Set,* and *Sixteenth Set*, where each iteration halves the number of cross sections contained in the total structure. The implementation of this method is compared with the structural weight metric described in Section 2.2.3. Section 3.2 will explore the tradeoffs between member size consolidation and structural weight.

2.5 Summary of Metrics

This chapter introduced parametric modeling methods used to implement geometric and topological randomization of a two-dimensional steel façade system. Measurement of well-understood structural performance objectives are explained and original metrics associated with constructability performance are introduced. All metrics are summarized in Table 2.1, which includes the complexity of metric implementation, as well as a fidelity rating of each metric.

The fidelity rating is based on each metric's likelihood to improve constructability based on the calculations provided. For example, it was discussed in Section 2.3.1 that the standardization of member length is not necessarily a valid measure of constructability, as member lengths are not likely to be standardized or consolidated by this calculation. Thus, this metric receives a low fidelity score. However, satisfying imperative constructability constraints, such as access to welds and tool clearance, is a requirement for ease of construction. For this reason, the Node Angle Connectivity metric receives a high fidelity score, as it applies a necessary constraint to primary structural components.

The following chapter explores tradeoffs associated with the two metric classifications, identifying structural characteristics which define trends and tradeoffs.

Metric	**Description**	**Class**	**Abbr.**	**Goal**	**Implementation Complexity***	**Fidelity†**
S1	Lateral Deflection	*Structural*	*LD*	*Ensure structural feasibility*	2	A
S2	Strain Energy	*Structural*	*SE*	*Measure structural efficiency*	2	A
S3	Structural Weight	*Structural*	*SW*	*Measure structural efficiency*	2	A
1	Standardized Length	*Constructability*	*SL*	*Improve Fabrication*	3	C
2	Trucking Requirements	*Constructability*	*TR*	*Minimize shipping costs, enhance site logistics*	2	B
3	Field Connections	*Constructability*	*FC*	*Improve on-site erection procedures*	2	A
4	Node Member Connectivity	*Constructability*	*NMC*	*Reduce shop fabrication complexity, improve on-site erection procedures*	2	B
5	Node Angle Connectivity	*Constructability*	*NAC*	*Introduce feasibility constraint for fabrication and erection*	1	A
6	Cross Section Variation	*Constructability*	*CSV*	*Simplify fabrication process and erection*	2	A
Other	Standardize Member Sizing	*Constructability*		*Implement standardization to simplify fabrication and erection processes*	1	A

**Complexity Rating: 1 – High, 2 – Moderate, 3 – Low; †Fidelity Rating: A – High, B – Moderate, C – Low*

***Table 2.1:** Summary of structural and constructability performance metrics, including goals for implementation, complexity ratings, and fidelity ratings.*

CHAPTER 3:
Evaluating and Characterizing Constructability Tradeoffs

This section evaluates the data collected from the multiple constructability and structural objectives described in Chapter 2. The multi-objective spaces indicate that strong tradeoffs exist between the two different classifications of metrics: structural performance and constructability. These tradeoffs are evaluated through quantitative analysis and qualitative design characteristics.

3.1 Characterizing Structural and Constructability Metrics

This section explores the quantitative scoring distribution of each metric and identifies key characteristics contributing to each metric's performance.

3.1.1 Structural Metrics

As previously outlined in Section 2.2, each design is evaluated based on three structural performance metrics: *Deflection*, *Strain Energy*, and *Structural Weight*. Because only truss elements are used, all three structural performance metrics trend very similarly in the objective space. Figure 3.1 includes histogram plots of normalized scores for a sample size of 2,000 designs. To normalize all scores, all values have been divided by the best performing data point in each metric, where a score of 1 indicates optimal performance.

The best and worst performing designs have been included in Figure 3.1, where the best design receives a normalized score of 1, and the worst design ranges anywhere from 10 to 260 times worse than the optimum score. Based on the following, several key attributes of high performance verses low performance can be concluded. All low performing structures can be attributed to lack of diagonals, or too many quadrangles. This leads to global instability of the structure. In contrast, high performing structures have a high density of members making up small, triangular areas. This leads to a more stable structure with even distribution of forces and higher levels of indeterminacy.

Analysis of the data presented in Figure 3.1 indicates that all three structural performance metrics trend similarly with very similar characteristics defining high verses low performance. For this reason, constructability metrics will be compared with the *Structural Weight* metric, as a representation of overall structural performance. This also ensures that *Structural Weight* and all constructability metrics are based on the same member sizes, as outlined in Section 2.2.3.

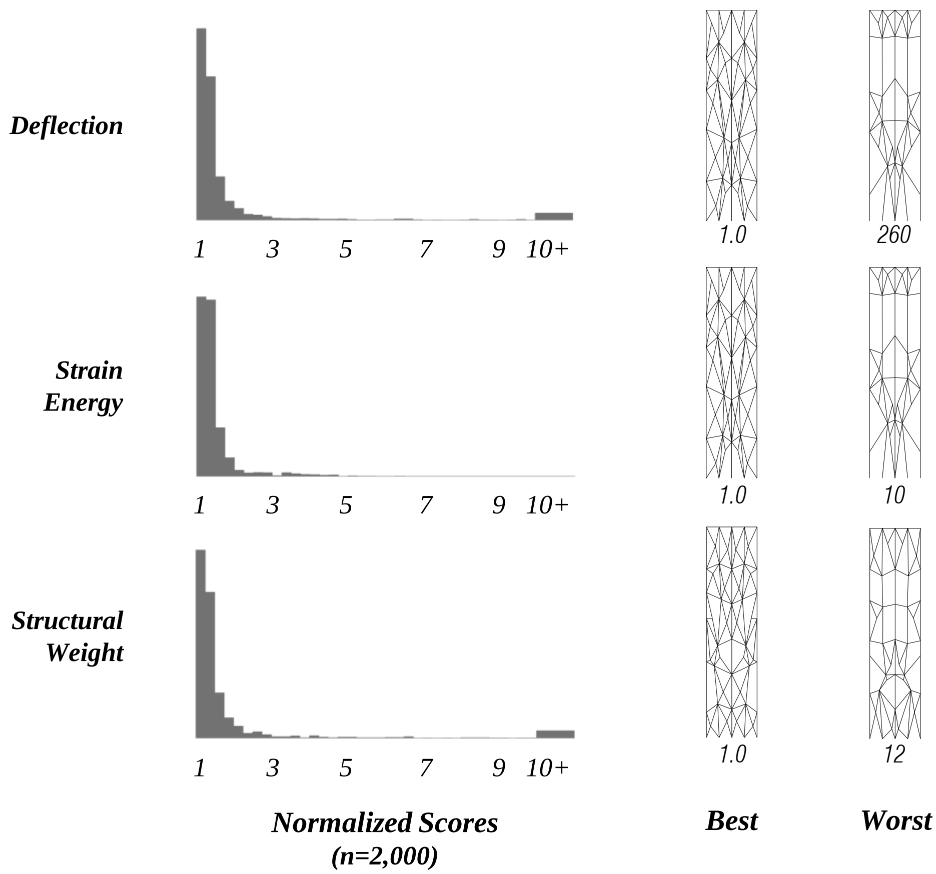


Figure 3.1: *Distribution of normalized structural scores with a sample size of 2,000 designs. The best and worst designs for each metric are shown, where lower scores are optimal and higher scores indicate worse performance.*

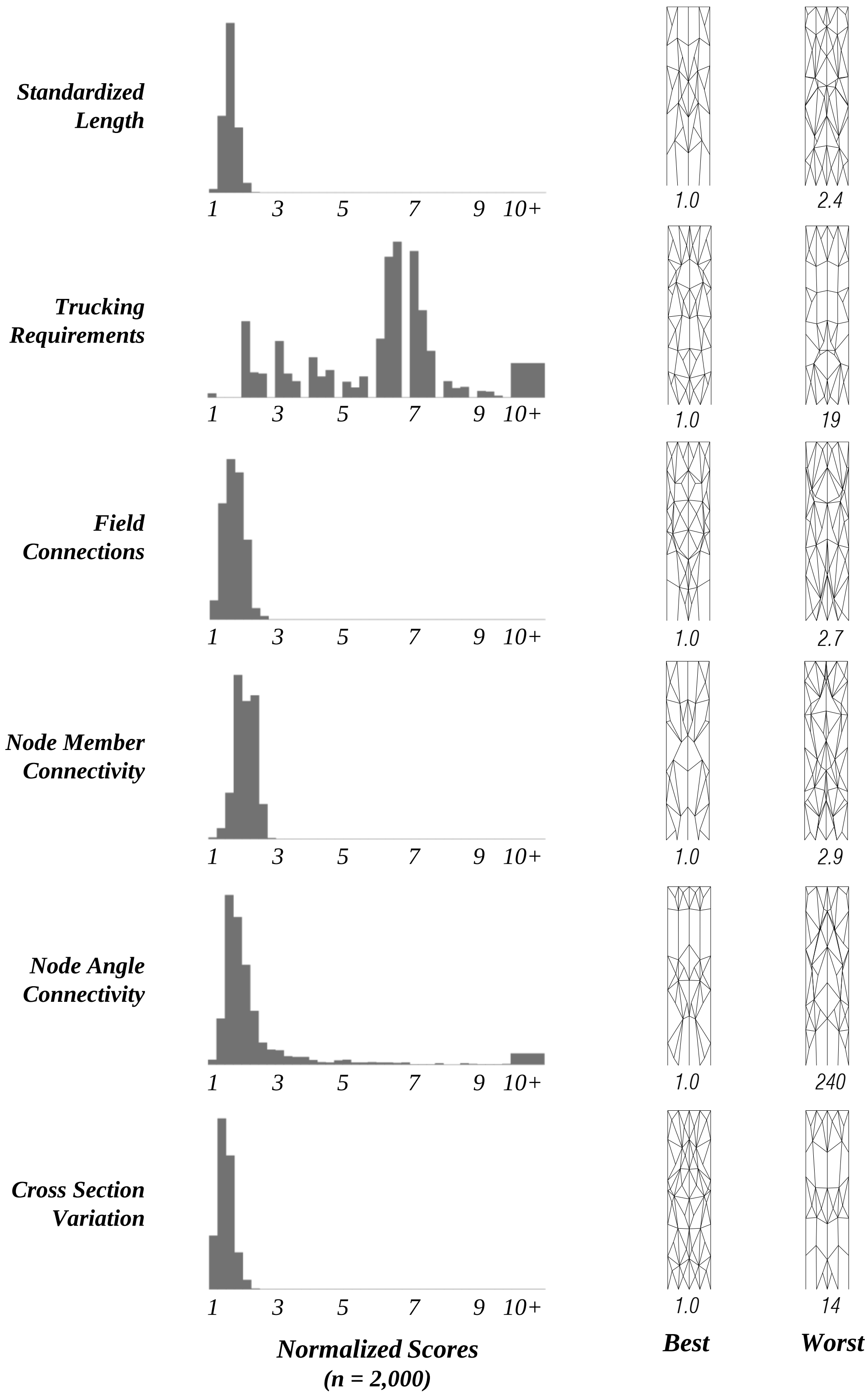


Figure 3.2: *Distribution of normalized constructability scores with a sample size of 2,000 designs. The best and worst designs for each metric are shown, where lower scores indicate higher performance.*

3.1.2 Constructability Metrics

Similar to the evaluation performed for structural metrics, the same 2,000 designs are evaluated based on the constructability metrics defined in Section 2.3: *Standardized Length, Trucking Requirements, Field Connections, Node Member Connectivity, Node Angle Connectivity,* and *Cross Section Variation*. Figure 3.2 shows the distribution of the normalized scores as well as the best and worst performing designs for each metric.

There are several global trends that are realized by comparing the best and worst designs for constructability and structural performance. Four constructability metrics have the opposite characteristics for high and low performing structures as structural performance: *Standardized Length, Field Connections, Node Member Connectivity,* and *Node Angle Connectivity.* For each of these three designs, high performance can be attributed to designs with fewer members and a high number of quadrangles. In contrast, low performance is attributed to a very high density of structural elements. For example, as seen in the *Node Angle Connectivity* and *Node Member Connectivity* metrics, low performing or infeasible designs have a high number of acute angles between members.

This data also shows that there are two constructability metrics, *Trucking Requirements* and *Cross Section Variation,* have very similar characteristics for high and low performance as the previously explored structural metrics. For these metrics, high performing designs have a very high density of elements that make up primarily triangular components, while low performing designs have more quadrangles and very few elements.

The general trends observed in this data implies that there are significant tradeoffs between constructability and structural performance. The following section explores these trends in greater detail.

3.2 Structural and Constructability Design Tradeoffs

Constructability and structural metrics are compared on bi-objective plots, indicating tradeoffs of varying significance between the two objective classifications. Figure 3.3 shows all six constructability metrics plotted against the structural performance metric, *Structural Weight.* In each plot, with constructability performance plotted on the y-axis and structural performance plotted on the x-axis, the designs reach a point at which constructability cannot improve without sacrificing structural performance. Though tradeoffs are minor for several metrics, such as *Trucking Requirements* and *Cross Section Variation,* graphical exploration of these metrics highlight structural components that are consistently characteristic of high performance.

In Figure 3.3, tradeoffs are identified using a Matlab culling function that utilizes algorithms to identify non-dominated solutions along the Pareto optimal frontier in the multi-objective space (Cao, 2008). Both global (seven objectives) and local (bi-objective) Pareto optima are identified in each plot. Clear tradeoffs are realized when considering *Standardized length*, *Node Member Connectivity*, and *Node Angle Connectivity* verses *Structural Weight*, while minor trade-offs exist between *Field Connections and Cross Section Variation* metrics when compared with structural performance. It is important to note that, in most cases, designs performing 50 percent worse than the optimum structural performance are often globally unstable, and therefore infeasible. These designs are excluded from all graphical sampling.

To better understand the multi-objective interaction, the bi-objective comparison of *Node Angle Connectivity* verses *Structural Weight* is explored. The numerical tradeoffs presented in Figure 3.3 are compared graphically in Figure 3.4, where feasible designs are selected from the Pareto optima. From this graphical representation, it can be seen that designs with high member density perform better along the structural performance axis, while those with fewer members and increasing quadrangle shapes perform better along the Node Angle Connectivity axis. This affirms the trends identified in Section 3.1, where the designs along the Pareto frontier reflect the global behavior of each metric.

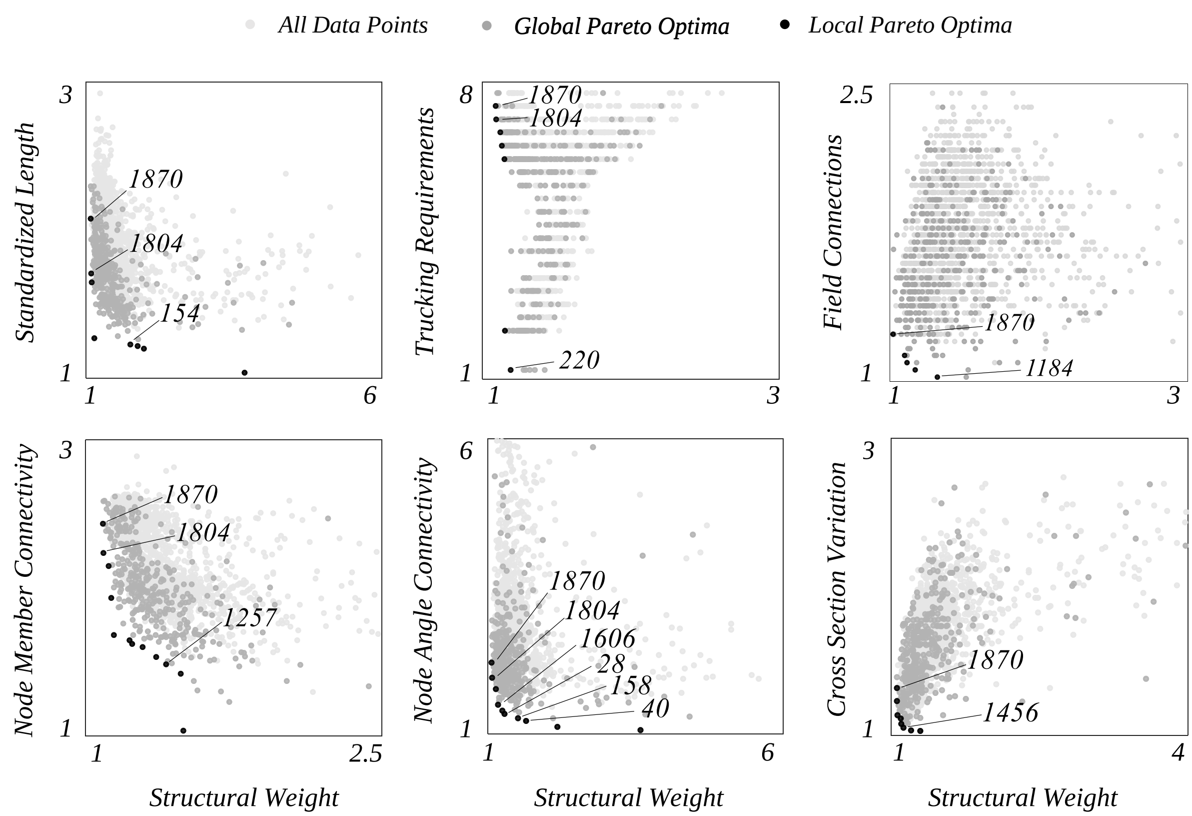


Figure 3.3: *Bi-objective plots comparing constructability performance on the y-axis verses structural performance on the x-axis.*

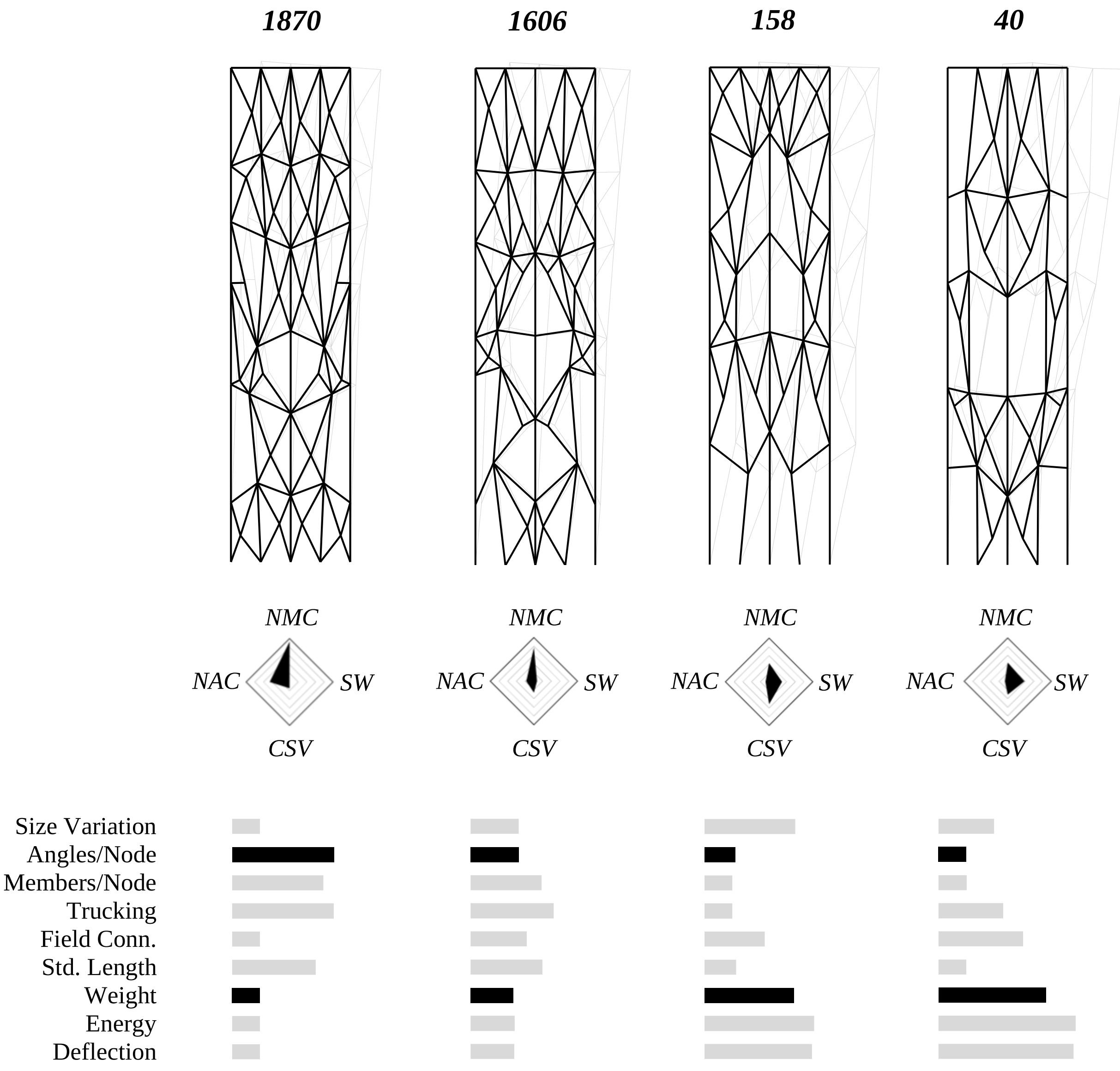


Figure 3.4: *Sample of Pareto optima from bi-objective plot comparing Node Angle Connectivity vs. Structural Weight. In the polygonal figures, minimizing the black surface area correlates to optimizing the metric along its axis. Similarly, in the bar charts, shorter bars indicate optimal scores and longer bars indicate worse performance for each metric.*

Figure 3.5 expands this graphical representation to the entire objective space, where Pareto optima are selected from all six bi-objective plots. Eight representative designs are selected, including top performing designs from at least one of the six objectives. Designs *1870*, *1804*, *1456*, *220*, *28*, *1184*, *1257* and *154* are arranged from left to right in order of decreasing structural performance. Though the trend from high member density to low member density is not entirely linear in this representative sample, tradeoffs can still be realized between several constructability metrics and structural performance.

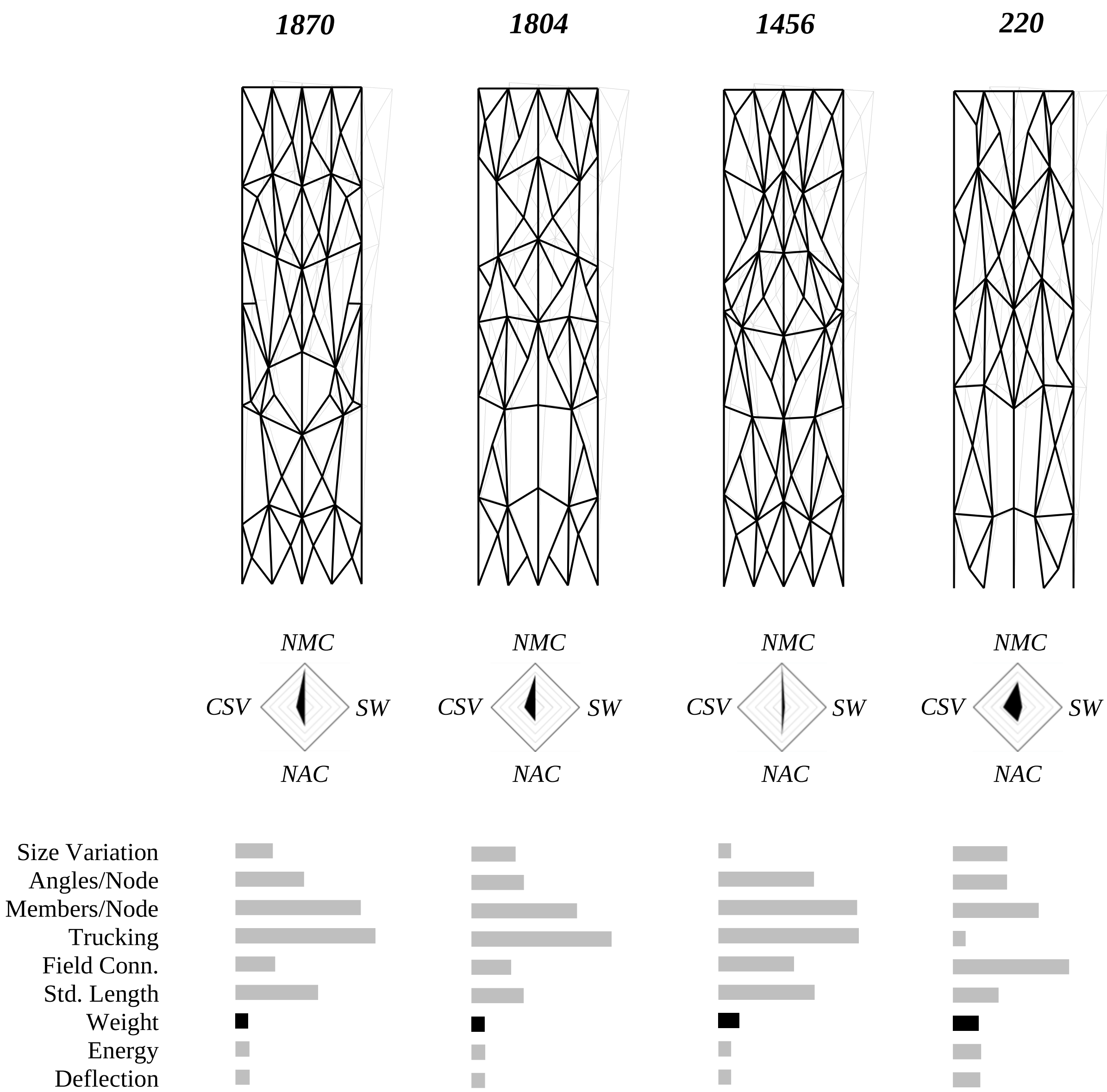


Figure 3.5: *Sample designs chosen along Pareto front, corresponding to various high performing designs for six constructability objectives in comparison to structural performance. Each design includes bar plots of each objectives' performance, where small bars corresponds to high performance and an increase in bar length corresponds to decreasing performance. Designs are arranged in order of decreasing structural performance, indicated by black bars. The polygonal shapes are a graphical interpretation of four objectives: Node Member Connectivity (NMC), Cross Section Variation (CSV), Node Angle Connectivity (NAC), and Structural Weight (SW). Well-performing designs minimized the black surface area.*

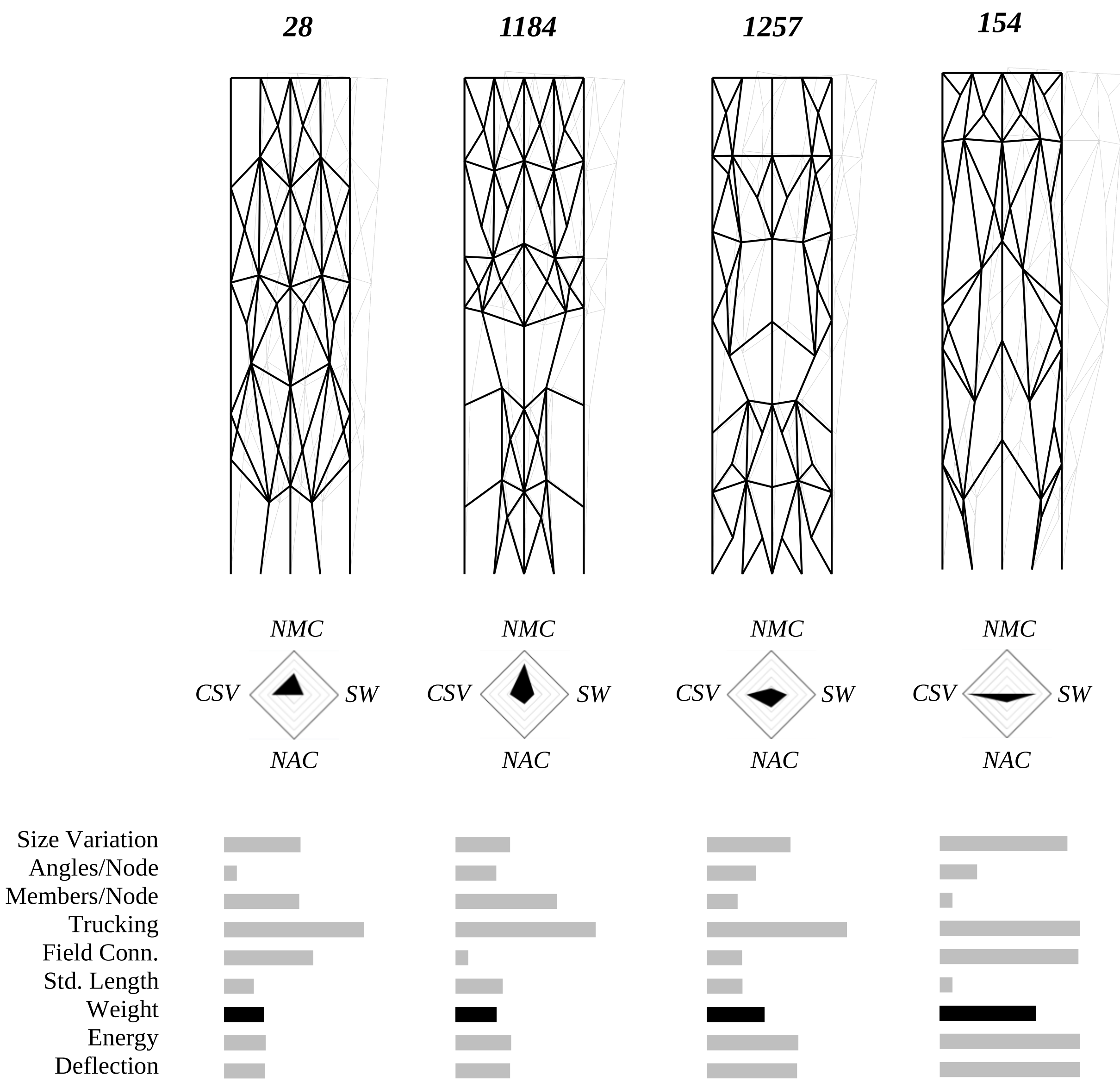


Figure 3.5 Continued: *Sample designs chosen along Pareto front, corresponding to various high performing designs for six constructability objectives in comparison to structural performance. Each design includes histogram plots of each objectives' performance, where small bars corresponds to high performance and an increase in bar length corresponds to decreasing performance. Designs are arranged in order of decreasing structural performance, indicated by black bars. The polygonal shapes are a graphical interpretation of four objectives: Node Member Connectivity (NMC), Cross Section Variation (CSV), Node Angle Connectivity (NAC), and Structural Weight (SW). Well-performing designs minimized the black surface area.*

3.3 Impact of Standardization on Structural Performance

Using the methodology described in Section 2.3, standardization of constructability components in truss façade systems is explored. Figure 3.6 shows the results of the standardization of structural member cross sections in 2,000 sample designs. As anticipated, based on the comparison made in Section 3.1, variation of cross sections and structural weight trend linearly when considering only individual sets of cross sections. However, when considering the global behavior of these two objectives, a minor tradeoff exists between *Cross Section Variation* and *Structural Weight*.

As the number of cross sections in a given structure is decreased, the overall weight of the structure increases. This increase, however, is relatively minor in comparison to the significant improvement in constructability. Figure 3.6 indicates that the number of different cross sections in a structure are reduced by a factor of 10, while the structural weight increases by a factor of 2. This implies that significant labor and cost savings can be achieved by consolidating cross sections, while the increase in the cost of material is marginal in comparison.

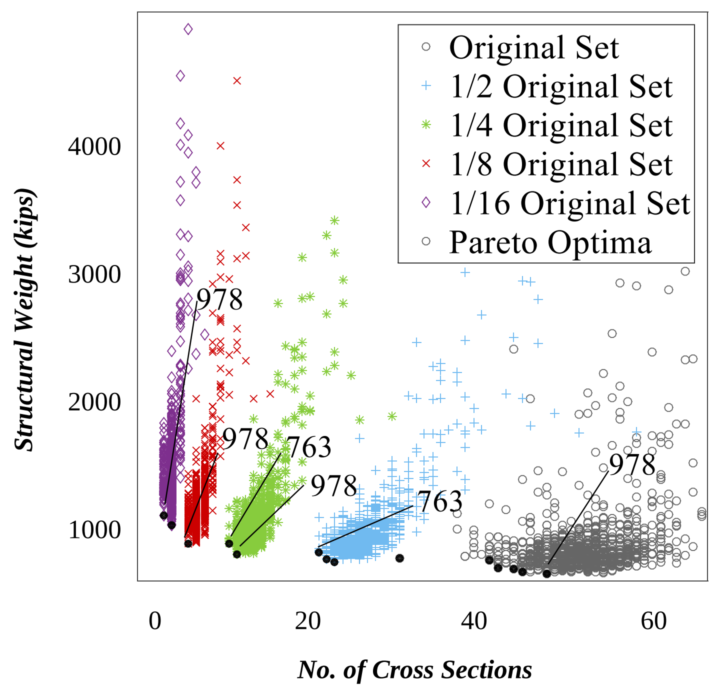


Figure 3.6: *Standardization of cross sections into consolidated sets compared with the structural performance metric, Structural Weight.*

Further, Figure 3.7 tracks several high performing designs in this bi-objective comparison to identify how size consolidation affects individual designs. This figure indicates that the standardization of cross sections yields very similar trends in each design. Further, designs that are not considered optimal in comparison of these two objectives trend nearly identically with those along the Pareto Frontier. These trends suggest that standardization of cross sections can be implemented up to the Quarter Set or Eighth Set before drastic increases in *Structural Weight* are experienced, regardless of overall structural performance.

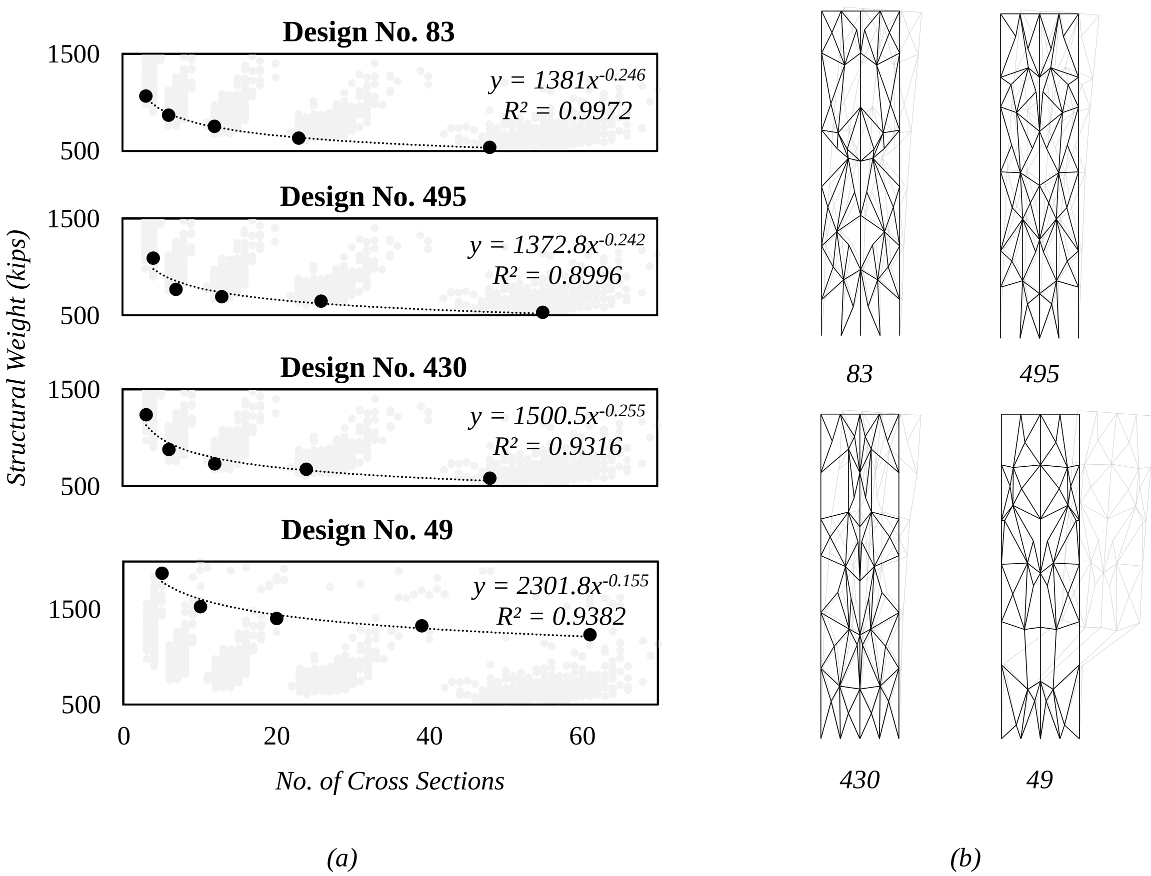


Figure 3.7: *Four designs selected from the data generated in Figure 3.5 indicating trends associated with Cross Section Standardization.*

3.4 Practical Implications and Implementation

In Chapter 3, the interaction between structural performance and constructability reveals that strong tradeoffs exist between these two metrics. Several main characteristics, including member density and nodal constraints, are primary contributors to performance along this interface. Balancing these two primary objectives in conceptual design is an important step, as optimization of one objective is likely to negatively impact the other.

Most metrics presented provide a reasonable measure for constructability and can be further developed to capture specific project details, including fabrication procedures, trucking or shipping constraints, and site logistics. Within the framework presented, weighting scales can be modified and known fabrication or logistical constraints can be implemented to increase the accuracy of each metric. These objective metrics can aid in designer exploration of a multi-objective design space by considering constructability constraints that are independent of project phase, location, and contractor methods.

CHAPTER 4:
Conclusions

"It's necessary that we start to move away from an approach that is dominated by material efficiency and focus more on structural safety and constructability."

- *Ted Zoli* (Cho, 2012)

4.1 Summary of Contributions

This thesis develops six new constructability metrics and explores the standardization of key structural components. Chapter two outlines the development of a randomized parametric framework used to explore optimization of a multi-objective design space which evaluates performance of designs based on constructability and structural objectives. Original constructability metrics have been quantified objectively, based on structural characteristics and geometry, rather than subjectively via behavioral modifications or informational databases. These metrics allow for designer interaction with construction-oriented goals early in conceptual design when primary structural systems are explored.

When comparing these original metrics with well understood measures of structural performance, significant tradeoffs are realized between the two objective classifications. Standardizing elements such as node geometry and member sizing can have significant impacts on ease of construction while adversely affecting structural efficiency. The significance of such tradeoffs is evaluated in the exercise of standardizing cross sectional areas in comparison with the *Structural Weight* metric. This analysis reveals that significant improvements can be made in constructability by consolidating cross sectional areas of structural members without significant impact to the overall structural weight. This finding encourages designers to explore the design-construction interface from a global perspective to realize improvements to overall project objectives.

4.2 Potential Impact

As the architectural design process moves towards an integrated, multi-objective approach to infrastructure development, computational tools are adapting to improve the conceptual design process (Mueller, 2015). Though previous research continues to develop advanced optimization algorithms, such as the discrete variable optimization developed by Zhu, few have rigorously defined constructability objectives which can benefit from these advanced computational efforts (Zhu, 2014). Figure 4.1, for example, shows a contemporary New York City high rise which, although randomly generated, resembles the interesting configurations presented in this study for steel façade systems (Nouvel, 2007). As contemporary designs shift towards such unique and expressive shapes, a multi-objective exploration that incorporates the proposed constructability metrics can aid in the discovery of unanticipated, high-performing designs.

Figure 4.1: *Jean Nouvel's 53 W 53rd Street high rise building in New York, New York* (Nouvel, 2007).

4.3 Future Work

Building from the objective, quantitative constructability framework introduced in this thesis, there are several areas which can be developed further. First, the performance metrics introduced in this thesis can be applied to a broader range of structural systems including spanning trusses or branching systems. The constructability performance in a range of structures can be compared with structural performance to identify if similar tradeoffs exists. These metrics can also be compared with other important architectural metrics such as solar gain and lighting. The extent of tradeoffs can be quantified and trends can be validated through this exploration.

As previously mentioned in Chapter 2, the standardization of member length can be expanded to consider implementation of sets of lengths, similar to the consolidated sets of cross sectional areas explored in Section 2.5. However, regenerating structures with revised member lengths selected from the parent population proves to be very difficult computationally. A model which can construct designs based on predetermined member lengths, however, would be extremely applicable and beneficial, particularly in instances which call for use of salvaged or scrap parts.

Similar to the implementation of predetermined member lengths is the regeneration of models with standardized nodes. This relates closely to the fabrication complexity associated with the Transbay Transit Center presented in Chapter 1. By implementing a model which can consolidate node angle orientations into sets, the number of castings can be drastically reduced, and the benefit of standardization would be realized. While this thesis is a useful tool in establishing baseline metrics and performance comparison, implementation of standardization is an important step towards physical constructability improvements.

4.3 Concluding Remarks

Advances in analysis software and fabrication processes are allowing structures which were once infeasible to be designed and constructed. Current design processes and contemporary designs are trending towards collaborative approaches to generate these unprecedented, unique structures. Historically, structural efficiency is a satisfactory goal for design, but trends are shifting towards balancing multi-disciplinary objectives. This thesis constitutes an important step in empowering designers to explore these tradeoffs in a rigorous yet creative manner.

Appendex A:
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