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Leveraging network analysis to improve navigability of design standards

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Abstract

The utility of building design standards is a growing concern amongst construction professionals. Design standards continue to swell with updates, which makes ensuring all requirements are satisfied increasingly complex for users. Few tools exist for authors of standards to improve navigation for users. This study investigates the use of network analysis to understand the relationship between the organization of a standard and navigational complexity. A case study is presented of the reorganization of American Concrete Institute's (ACI) flagship design document, ACI 318. The standard's networks before (ACI 318-11) and after (ACI 318-14) the reorganization are developed via rule-based text extraction. Networks are analyzed assuming that ACI 318-14 is the structurally superior document. Indicators of complexity are identified from each networks' characteristic features, centrality metrics, clustering tendencies, recurring motifs, and geodesic paths. Network analysis is found to be useful for identifying, understanding, and mitigating navigational complexity within a building design standard.

Keywords: Building codes and standards; Complexity; Network analysis.

1 Introduction

Functional standards for the design and construction of building structures are essential for public health, safety, and welfare. Such standards, when enacted by regulations, cited in contract or construction documents, or otherwise required by an authority having jurisdiction, provide an important basis for trust between project stakeholders, including owners, designers, occupants, regulators, and ultimately the public at large. Building design standards are unique compared to other industry standards in that while compliant designs must be safe, full-scale prototype testing is rarely practical [1]. To serve their purpose, ideal standards are clear and unambiguous, such that all stake-holding parties interpret them similarly.

Many professionals in architecture, engineering, and construction believe that the utility of standards is being undermined by a steady increase in their complexity, and indeed, in some instances length [2-11]. Users often point to 'ratcheting' in which the documents' size, number of provisions, references to external standards, or reliance on other supporting documentation increases, as evidence that a standard is less functional than previous editions [12]. The organization of a standard document is critical to the user experience yet very little research has been conducted on implementing document organization that permits growth and expansion while minimizing user-perceived complexity.

Inherent tension exists between the size of the document and the ease with which it can be navigated, yet standards-writing bodies (SWB) are compelled to encode in standards an ever-growing number of requirements. Society's definition of "public health, safety, and welfare" continues to evolve to include new metrics associated with sustainability and social justice, to name just two [13]. Furthermore, the effects of climate change require modernizing standards to address new or more frequent and extreme hazards [14]. Efficiently developing new standards for context-appropriate non-conventional materials or methods as they emerge to address these challenges is also necessary [15]. The individuals comprising SWB are themselves end users who [often] volunteer their valuable time and other resources to the standards-writing process. Nonetheless, few tools are available to aid authors and SWB in developing, evaluating, or improving the utility of their standards. It is specifically to these stakeholders that the content of this study is intended.

The present study contends that for design standards, size alone is a poor measure of navigational ease-of-use (or its obverse, navigational complexity). Network analysis techniques are developed as a tool for helping to mitigate complexity through the measurement of topological features

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*Corresponding author: Kent Harries, E-mail: kharries@pitt.edu of a standard. Such features indicate areas of complexity and provide a rational basis for comparisons between potential alternatives. In this paper, the authors demonstrate this approach by examining a case of building code reorganization: ACI 318. Trends from this case study are thought to be extendable to other design standards albeit limited to those with similar design workflow and maturity.

2 Literature review

Building standards are (typically) mandatory-language documents, printed on paper or digital paper facsimile, with a hierarchical structure composed of chapters, sections, and individual provisions each with a progressively narrowing scope related to some building element, design procedure, or anticipated behavior. Source provisions direct users, via references, to target provisions in the standard that are co-requirements or are otherwise related to the task at hand and should be investigated by the user to ensure compliance. Some provisions will reference external standards. References can be explicit (i.e., naming the referenced provision or external document), implicit (sequential provisions or the requirement of an input parameter or variable from another provision), or silent (provisions that are dependent in some way but not explicitly or implicitly associated). Although the purpose of references is not to guide an end-user through the document, per se, they are understood to heavily influence navigation and the user experience.

An intuitive organization and reference structure can enable users to easily identify, locate, and interpret standard provisions for the task at hand, ensuring efficient use of resources, higher confidence in achieving conformance, and greater user satisfaction with the standard [16]. A poorly organized standard can cause confusion for the user and lead to misinterpretation, unsatisfied requirements, and potentially unsafe designs [3, 17]. Users are less likely to satisfy dependent requirements if references to these are absent. Conversely, if all tangential provisions are referenced by a source provision, a user is obligated to investigate each provision and the value of the references is lost. Moreover, the organization of a standard can cause confusion in the authoring phase with the SWB omitting requirements and creating logic errors or requirement loops that cannot be satisfied [18].

A standard can be abstracted as a network of information, where nodes represent provisions, requirements, or variables (depending on model granularity) and their various relationships are represented by edges. Previous network representations of building design standards, largely developed before 1980, noted limitations imposed by network understanding, computationally intensive algorithms, hardware capabilities, and the manpower-intensive abstraction process [19]. Fenves et al. [18] decomposed the American Institute of Steel Construction (AISC) Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings [20] into four levels of increasing resolution: the organization (outline), information network, decision logic tables, and datums. Prior to a major restructuring of the standard, the information network model for the 1969 AISC Specification was used to visually inspect the standard for circular references in the network. Nyman et al. [17] expanded the idea of information network representations of a standard into a ‘functional-organizational’ network, where functions are mapped as edge-connecting datums. A complete functional network representing all transformations of input data to output data for the entire 1969 AISC Specification was not completed. Rudimentary clustering algorithms were deployed but Nyman accurately predicted that their research likely wouldn’t be used to guide the Specification restructuring due to the many inconsistencies and limitations of the network model and algorithms of the time.

These works culminated in the development of the comprehensive Standards, Analysis, Synthesis, and Expression (SASE) methodology [21]. The American Concrete Institute (ACI) 318-77 document [22] was modeled using an early modified version of SASE [23]. Similarly, a version of SASE [24] was used to analyze the 1978 Applied Technology Council Tentative Provisions for the Development of Seismic Regulations for Buildings [25], but this work languished with the standard not being published in this form. This was the last known time an information network was built for the purpose of improving a building design related standard. Throughout the 1980s, research shifted away from authorship aid to design aid and automated code compliance checking [19]. With that shift, limited logic/network representations evolved into more abstract, and later ontological, representations of standards. These offered greater flexibility for wider applicability and potentially greater fidelity, and are better suited for automated code compliance checking. To date, no known research has been conducted relating the features of a building design standard’s information network model to ease-of-navigation by users. With modern network science and computing techniques many of the limitations of the past are overcome, making the time right to revisit network representations of standards. The intent of this paper is therefore to illustrate an approach to the network analysis of building standards; this is done through the use of a case study.

3 Case study description

The restructuring of ACI’s flagship document, *Building Code Requirements for Structural Concrete and Commentary (ACI 318)*, from the 2011 [26] to 2014 [27] editions provides an opportunity to compare the organization of two standards that contain otherwise essentially identical information and objectives. To minimize potential confusion caused by a significant reorganization of a national building standard, ACI intentionally introduced no substantive changes to content in this 2011 to 2014 reorganization. Although some provisions were split to accommodate the revised 2014 format, and some equations were converted to “lookup” tables or figures, the majority were left unaltered so as to not compound confusion anticipated by the reorganization [16]. The ACI 318 reorganization provides a case study of the effect that restructuring the standard had on users’ experience and provides a control for the influence that new or altered requirements may have on perceived ease-of-use. An overview of the 2011 to 2014 transition is reported by Ghosh [28].

A primary feature of the 2014 revision was the introduction of so-called "toolbox" chapters that collected commonly used provisions and – one assumes – reduced repetition of these within the document. A user experience survey [29, 30] found respondents were able to discern between affected and unaffected qualities of the standard and perceived navigation improvements. Respondents showed a slight preference for the revised 2014 edition. Based on the reported survey as well as ACI communications [31], the present authors assume ACI 318-14 to a be a superior document with respect to ease-of-use – allowing us to draw comparisons and highlight network features that may affect this improvement.

Characterizations and comparisons of the reference networks of each of the 2011 and 2014 versions of ACI 318 are presented in the following sections. Navigational complexity is investigated by linking the end-users' aggregate experiences to the structures of the standards' reference networks. The process followed is summarized in Figure 1. First, the pre-processing required to develop the network models from the standards' texts is described. Next, the models are investigated using general characteristics, centrality metrics, degree assortativity, clustering trends, recurring motifs, and geodesic paths – each approach is described in turn. Finally, discussion and conclusions are presented.

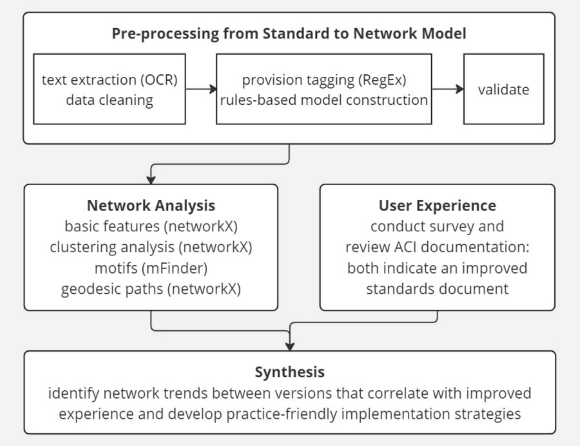


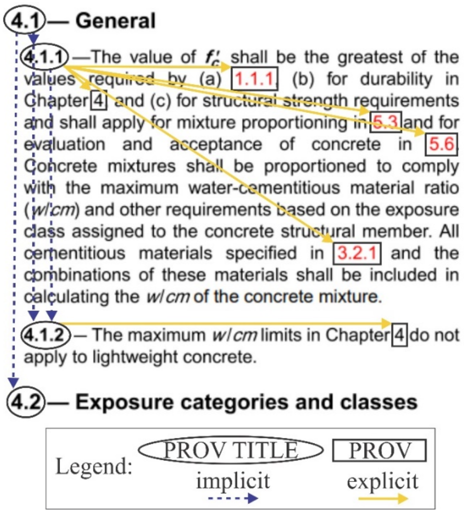
Figure 1. Research process map.

4 Model development

Text extraction and digitization of simple documents having a clearly defined objective, such as restaurant menus or instruction manuals can be accomplished reliably and almost instantaneously with most smartphones. The challenges extracting text from building design standards arise from (1) their large size; (2) the presence of extraneous information on many pages; (3) identifying and representing tables and other graphical presentations; (4) identifying and representing symbols and equations; (5) corrupted or incorrect file metadata; (6) maintaining relationships during extraction (i.e., provision title and content); and, (7) validation of the extraction.

The ACI 318-11 [26] and ACI 318-14 [27] documents were obtained in Adobe Portable Document Format (PDF). To extract the text from the documents, the Python (v3.8) package PyMuPDF (v1.21.1) was used to first crop pages to eliminate the adjacent commentary, headers, and footers. Tables and figures are a continuation of provisions and are therefore captured in the implicit network. Tables and figures were algorithmically detected and their content excluded from analysis, resulting in minor errors of omission due to some outgoing explicit references. Explicit references targeting tables or figures were considered to target the items' parent provision. The remaining text was extracted to a plain text file and cleaned to a uniform state (i.e., consistent new line characters between each provision) using substitutions facilitated by regular expressions.

Only the standards' provisions are considered in this analysis, resulting in a relatively low-granularity model. Labels were assigned to the text based on regular expressions pattern matching. Network graphs were created based on the labels as shown in Figure 2, with each node representing a provision title [PROV TITLE] and each explicit reference edge in the network representing the directed relationship between the initiating [PROV TITLE] and the referenced provision [PROV].


4.1— General

4.1.1—The value of f'_c shall be the greatest of the values required by (a) 1.1.1 (b) for durability in Chapter 4 and (c) for structural strength requirements and shall apply for mixture proportioning in 5.3 and for evaluation and acceptance of concrete in 5.6 Concrete mixtures shall be proportioned to comply with the maximum water-cementitious material ratio (*w/cm*) and other requirements based on the exposure class assigned to the concrete structural member. All cementitious materials specified in 3.2.1 and the combinations of these materials shall be included in calculating the *w/cm* of the concrete mixture.

4.1.2— The maximum *w/cm* limits in Chapter 4 do not apply to lightweight concrete.

4.2— Exposure categories and classes

Figure 2. Reference network model development on excerpt from ACI 318-11 [26].

In the resulting reference network models (the example of ACI 318-11 is shown in Figure 3 to provide the reader a sense of the size and complexity of the networks developed and subsequently analyzed), provisions are represented by nodes and their relationships represented by edges. Edges are directed when the relationship operates in only one direction, such as a provisional reference, which cannot be traced backwards. For this research we attribute "explicit" to an edge, e_{ij}, initiating from the provision at node i which explicitly references the provision at node j. We attribute "implicit" to an edge representing the sequential 'flow' from the root of the first chapter to all other chapters and sequentially through each chapter until reaching "leaf" nodes, which point to no further provisions. The directed graph representation of a standard is therefore represented by an explicit network, an implicit network, and a complete network when explicit and implicit networks are combined.

The initial chapters of ACI 318, which contain few references or are glossaries, were excluded from analysis as were references to external codes, standards, or other documents. The co-occurrent relationships between provisions that simply mention or require action on the same datum (i.e., a variable or general topic), were not captured. The nodes in the implicit networks were validated 'by hand' as being complete. The set of edges in the implicit networks was developed algorithmically utilizing rules derived from the structure of the node labels and similarly validated. The set of edges in the explicit network was developed by regular expression pattern matching and were not strictly validated.

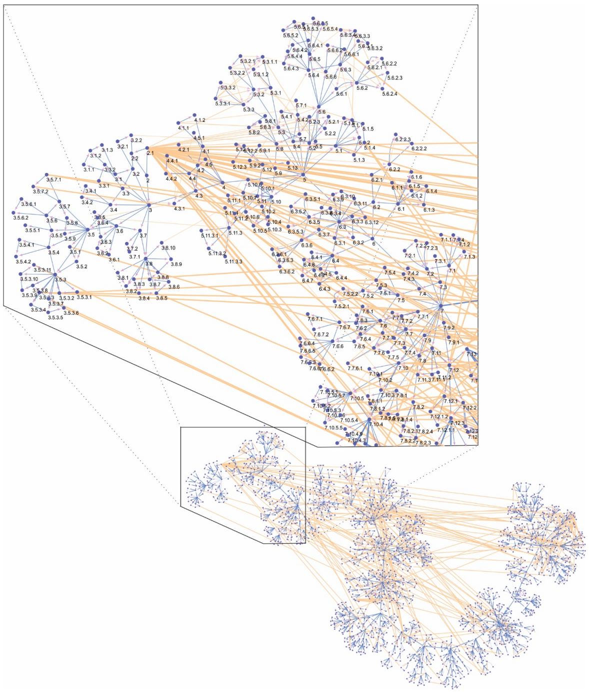


Figure 3. Reference information network of ACI 318-11 [26]. Organic layout based on implicit network (blue) with explicit references (gold) overlaid.

5 Network analysis

Networks are versatile abstractions applicable across many fields of science. For this reason, a variety of network features are reported in the literature, although it is not immediately clear which may be related to navigational complexity in building design standards. Implicit and complete reference networks are considered separately to better understand the effect of the added explicit references on connectivity. In the implicit network, and by extension the complete network, all nodes should be reachable from the root node; this is known as a connected graph. The explicit network is likely not connected, therefore some metrics that depend on connectivity (e.g., characteristic path and diameter) cannot be calculated for the explicit network alone. A substantial review of network metrics is presented by Newman [32]; a complete review of these relevant to the present study is reported by Rogers [30]. Table 1 summarizes several fundamental characteristics of the ACI 318-11 and ACI 318-14 reference networks, as well as various connectivity features. Features identified in Table 1 are described subsequently.

ACI 318-14 increased, with respect to ACI 318-11, in size both in terms of the number of nodes and edges, however the number (and proportion) of explicit edges and nodes is reduced. Similarly, the lengths of both the characteristic path (the average geodesic path) and diameter (the longest geodesic path) increase after the revision indicating increased connectivity. All nodes that can reach each other form 'strongly connected components', which is not possible in the directed implicit network. After the revision, the largest strongly connected component fraction decreases, indicating decreased connectivity or increased modularity. These trends imply that the 2014 revision has had a select effect on connectivity, preferential to the forward direction of 'flow'. In other words, users can potentially encounter longer paths through ACI 318-14, but they are more likely to be directed 'forwards' (confirmed by the explicit direction ratio being greater) or 'deeper' into the implicit hierarchy towards some end. Before the 2014 revision, 'backwards' explicit references created cycles and larger strongly connected components: it was likely more challenging for users to exhaust provisions of a design instance. This exhaustion of provisions is potentially important since it indicates to the user that the design is, in fact, 'complete'; that is, that no provisions are inadvertently omitted.

Table 1. ACI 318-11 [26] and ACI 318-14 [27] network feature summary.

Network	**ACI 318-11**	**ACI 318-14**
Pages in PDF	509	524
Nodes (ACI 318-11 shown in Figure 2)	1876	2368
Edges (ACI 318-11 shown in Figure 2)	4638	5175
Implicit edges (% of total edges)	3284 (71%)	3978 (77%)
Explicit edges (% of total edges)	1354 (29%)	1197 (23%)
Explicit direction (forward: backward)	0.80 (601:753)	1.31(680:517)
Explicit active nodes (% of total nodes)	1113 (59%)	1215 (51%)
Largest strong component fraction	0.604	0.390
Average degree	4.9	4.4
Characteristic path length (mean geodesic)	11.0	13.3
Diameter (longest geodesic)	32	49
Power Law exponential	0.388	0.394
Degree assortativity – implicit (jackknife error)	0.057 (0.042)	0.106 (0.044)
Degree assortativity – complete (jackknife error)	0.061 (0.031)	0.055 (0.034)
Clustering Coefficient (mean/median)	0.274 / 0.166	0.245 / 0.333
Average node depth in implicit network	3.28	3.63

5.1 Centrality metrics

The centrality of a node (or edge) is a measure of its importance to the network. Since there are many ways to define importance, there are a variety of ways to measure centrality [33]. Centrality is generally calculated for a node by considering either the volume or lengths of paths containing the node. Radial centralities consider paths where the node being analyzed is the start or end of the path, while medial centralities consider all paths that pass through the node under analysis, including those beginning and ending at the node.

5.1.1 Degree centralities

Degree centralities are among the simplest properties of a network to extract and can be illuminating to the performance of the network. For directed graphs, edges are characterized as incoming or outgoing (relative to a node) and counting these directed edges gives the nodal metrics 'in-degree' and 'out-degree', respectively. Three degree distributions are observed for directed graphs (Figure 4): the total-degree, in-degree, and out-degree distributions. The distributions represent the probability, *P(k),* that a node in the network is connected to *k* other nodes.

Much like the distributions shown in Figure 4, degree distributions in other real networks commonly skew right and demonstrate exponential decay as the degree increases [32]. Across all three distributions, ACI 318-14 has a slightly lower average degree (values shown in figure legends) compared with ACI 318-11, indicating fewer references per provision. The total-degree distribution shows a significant increase in leaf nodes (those having in-degree of 1 and out-degree of 0) from ACI 318-11 to ACI 318-14. Leaf nodes only exist in sub-clauses with no explicit references, no sequential (i.e. lateral) sub-clauses fore or aft, and no succeeding provision. This trend between versions of ACI 318 indicates increased modularity, which may serve as a mechanism for decoupling standard requirements.

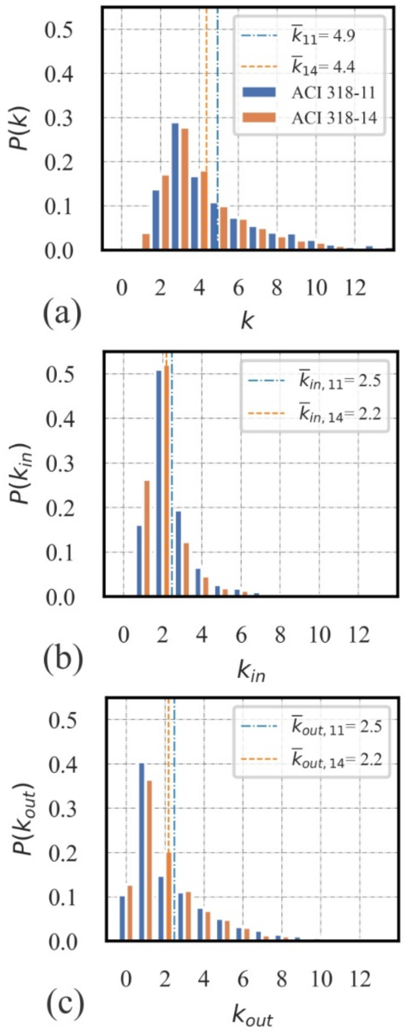


Figure 4. ACI 318 [26, 27] complete networks (a) total (k), (b) in-degree (k_{in}), and (c) out-degree (k_{out}) probability distributions. (Horizontal-axes are truncated for clarity).

Provisions with high degree centrality have specialized roles in both ACI 318-11 and 318-14. Clause B.18.1.3 in ACI 318-11, for instance, references an extensive list of provisions that "shall not apply" when the alternate design approach of ACI 318-11 Appendix B is adopted. Similarly, in ACI 318-14, clause 18.2.1.6 references provisions necessary to satisfy special seismic-force-resisting requirements for various system types. Considering degree as a measure of centrality, those nodes with a relatively large number of explicit references are important for end-users; in these cases, they are 'roadmap' clauses, for instance. It is of note that ACI 318-11 Appendix B underwent a major technical change in the 2014 revision and was largely absorbed into the main body of the standard.

5.1.2 PageRank centrality

PageRank is a scoring algorithm developed by Google to rank search results that match a user's query [34]. The algorithm is a natural extension of eigenvector and Katz centrality measures [32]. The premise of PageRank centrality, which is a radial and volume-based metric, is that if important source nodes point to a target node, then the target node is also important. PageRank centrality is similar to degree centrality but instead of rewarding a single point to a node for each of its neighbors, the algorithm weighs the connections by the importance of the neighbors (i.e., their own centrality).

The PageRank centrality of each node *i*, $C_{PR}(i)$, is proportional to the sum its neighbors' scores divided by their out-degree:

$$C_{PR}(i) = \alpha \sum_{j} A_{ij} \left(\frac{C_{PR}(j)}{k_{out}^{j}} \right) + \beta_i \tag{1}$$

where: **A** is the adjacency matrix, whose elements are defined:

A_{ij} = **1** if there is an edge *from node j to node i*, and **0** otherwise.

k_{out} is a node's out-degree. If a node has out-degree of zero, by convention k_{out} = 1 and A_{ij} = 0 so the node does not contribute to the summation.

α is a normalizing constant less than unity; 0.85 was used here; and,

β is the rank source factor taken as 1/*N* in which *N* is the total number of nodes.

There is an increase of the proportion of nodes within the lowest bin of scores from ACI 318-11 to ACI 318-14, shown in Figure 5, which is most likely due to the greater number of nodes in the ACI 318-14 network. The results presented here do little to add to one's understanding of either network's structure or important nodes therein. However, the PageRank algorithm is well-studied and can be extended to consider node and edge properties, including semantic relations; this should be considered for future study. In the surfer model [34], the β parameter relates to the likelihood that an end-user jumps to a particular node when becoming 'trapped' or 'bored'. Here β is uniformly distributed, but an alternative implementation could give nodes higher on the implicit hierarchy a greater β-value. Intuitively, this more closely mimics how a user is likely to use a standard – being more likely to jump to higher-level topics than to provisions deep in the hierarchy. The PageRank algorithm can also be modified into the so-called query-dependent PageRank (QD-PageRank), where the β parameter for each node is tuned based on the node's relationship to a user query or a topic [35].

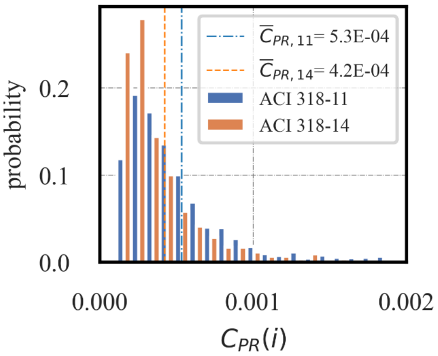


Figure 5. ACI 318 [26, 27] complete networks PageRank centrality (CPR) probability distribution.

5.1.3 Hubs and authorities

PageRank centrality only awards high centrality to a node if it is *targeted* by a node with high centrality. However, sometimes a node that *targets other* nodes is important, *even if few important nodes target it*. The Hyperlink-Induced Topic Search (HITS) algorithm distinguishes two types of important nodes in the network; authorities, to which many nodes point, and hubs, which point to many nodes [36]. With respect to the internet or other hyper-linked spaces, authorities are thought to house useful information, while hubs are important for locating those authorities. Nodes can simultaneously be hubs and authorities and the best hubs identify where the best authorities can be found.

The authority centrality is defined as:

$$C_a(i) = \sum_j A_{ij} C_h(j) \tag{2}$$

Similarly, the hub centrality is defined as:

$$C_h(i) = \sum_j A_{ji}\, C_a(j) \tag{3}$$

HITS is an iterative algorithm. Also note that the adjacency matrix elements are indexed A_{ji} rather than A_{ij}, in Equation 3, so that a hub (source) is defined by those nodes pointed to (targets).

Figure 6 shows top hubs and authorities in ACI 318-11 and ACI 318-14 as determined by the HITS algorithm. ACI 318-11 has several hotspots of hubs and authorities (Chapters 10, 12, 14, 18 and Appendix B in Figures 6a/b), while ACI 318-14 appears to have only one major hotspot (Chapter 18 in Figures 6c/d). The hotspot chapters identified in ACI 318-11 were some of the most heavily revised for 2014, while Chapter 18 – *Seismic Design* in ACI 318-14 is consistently a work a progress. HITS is not identifying 'important' hubs and authorities so much as identifying atypical referencing between provisions, highlighting areas that have special function but also those potentially in need of reorganization or revision.

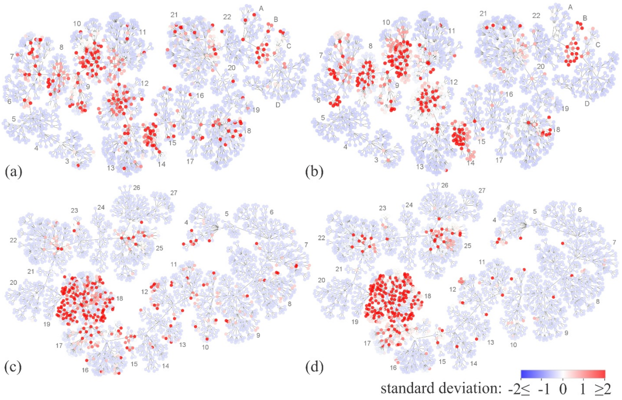


Figure 6. ACI 318-11 [26] [(a) hub, (b) authority] and ACI 318-14 [27] [(c) hub, (d) authority] complete network standard deviation of clustering scores.

5.1.4 Betweenness centrality

Betweenness centrality is a medial-volume metric of centrality that is dependent upon the fraction of geodesic paths that pass through a node. A geodesic path is the shortest path between a node pair. In messaging or transit networks, nodes with high betweenness can be interpreted as being important intermediaries or as useful shortcuts between two other nodes. Nodes with high betweenness in networks may exert influence through their control over information passing between other nodes (aka bottlenecks) [32]. The nodes with the highest betweenness are also those whose removal from the network will most disrupt flows through the network because they are transited most often. In a design standard, however, end-users are unlikely to take the geodesic path and betweenness may not be an appropriate measure of centrality in many cases.

Betweenness centrality, $C_B(i)$, of node i is the sum of the fraction of all pairs of geodesic paths g_{st} that pass through node i:

$$C_B(i) = \sum_{s \neq i \neq t} \frac{n_{st}^i}{g_{st}} \tag{4}$$

where: n^i_{st} is the number of geodesic paths from s to t that pass through i;

g_{st} is the total number of geodesic paths from s to t; and,

$n^i_{st} / g_{st} = 0$ by convention, if $g_{st} = 0$.

Explicit references have a significant impact on geodesic paths in the network and therefore have a significant impact on betweenness centrality. In all cases, explicit references in the complete networks shifts high betweenness scores from nodes near the geometric center of the networks closer to the outskirts. Nodes further from the center can now access nodes across the network via explicit referencing without passing through the center, resulting in shorter paths between said nodes. For example, there is a shift from high centrality from nodes 16, 17, 18 in the ACI 318-11 implicit network to 6, 7, 8 in the ACI 318-11 complete network. Nevertheless, there is little evidence that any of the high betweenness nodes should be considered "more important" than other nodes.

5.1.5 Closeness centrality

Closeness centrality is a medial-length measure of centrality based on the average length of geodesic paths through a node. Closeness centrality is sometimes criticized for not discriminating enough between nodes. The range of geodesic paths in the network typically will not vary significantly, so closeness centrality tends to create bins of importance. This means that closeness centrality scores are very responsive to changes in the network and that only the groups of nodes at the tails may have any robustness.

Closeness centrality, $C_c(i)$, of node *i* is the reciprocal of the average geodesic path distance to *i* over all *n* nodes reachable from *i*:

$$C_c(i) = \frac{n_i - 1}{\sum_j d_{ij}} \tag{5}$$

where: d_{ij} is the geodesic path distance between *i* and *j*, and, n_i is the number of nodes reachable from *i*.

Closeness may be a reasonable indicator of the relative importance of nodes after introducing explicit references. For both complete ACI 318-11 and ACI 318-14 networks, provisions that are important to design are identified [30]. The distribution for ACI 318-11 implicit network closeness centrality (Figure 7) is slightly flattened (average $C_{ci,11}$ = 0.0018, kurtosis = -0.14, skewness = 0.03) and is shifted positively compared to that of the ACI 318-14 implicit network (average $C_{ci,14}$ = 0.0014, kurtosis = -0.04 and skew = 0.281), which displays a slightly positive skew. Greater closeness centrality means a shorter geodesic path distance between nodes. An increased positive skew could indicate groups of nodes with specific intermediate or path-shortening roles. The effect of explicit references on the ACI 318-11 complete network is more dramatic when compared to the implicit network than for that of ACI 318-14 (Figure 7), potentially indicating compensation over a poor implicit network. High relative kurtosis in the ACI 318-11 complete network (average $C_{c,11}$ = 0.059, kurtosis = 6.01, skew = -0.062) versus ACI 318-14 (average $C_{c,11}$ = 0.031, kurtosis = 3.00, skewness = 1.17) indicates many nodes with the same level of access to the rest of the network. Based on this analysis it may be desirable for explicit references to have only a marginal effect on closeness centrality. Since closeness centrality scores are normally distributed (even when geodesic path lengths distribution has a long tail), the mean closeness centrality score may be a reasonable indicator of the impact of explicit referencing on the implicit network.

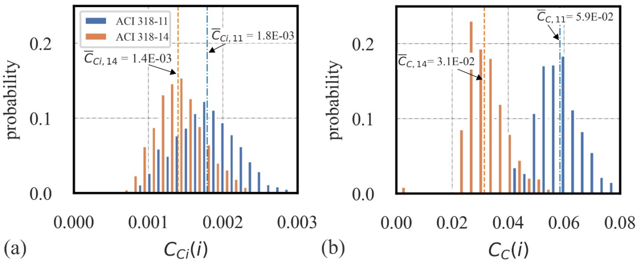


Figure 7. Closeness centrality probability distributions for (a) implicit (CCi) and (b) complete (CC) networks.

5.2 Clustering and motifs

The clustering coefficient, *C,* is a global metric of a network graph that reports the average probability that a node shares edges with two nodes*,* which already share an edge. This is sometimes called transitivity and effectively measures the density of subgraph triangles in networks [32].

The clustering score for an individual node *i*, *C(i)*, is the ratio of directed triangles of which node *i* is a part out of all possible directed triangles containing node *i*. Formally:

$$C(i) = \frac{(\boldsymbol{A} + \boldsymbol{A}^T)^3_{ii}}{2(k_i(k_i - 1) - 2A^2_{ii})} \tag{6}$$

where*:* k_i is the sum of in-degree and out-degree of node *i* and **A** is the adjacency matrix of the network (defined with respect to Equation 1).

The ACI 318-14 implicit network structure has a larger proportion of nodes with a cluster score of zero than does ACI 318-11 and, notably, the explicit network preserves these scores (Figure 8). Nodes with a zero score are typically subclauses deeper in the implicit hierarchy and do not have preceding or succeeding provisions (i.e., these nodes have an in-degree of 1). In line with the analysis of degree centrality, their preservation implies that a well-structured document protects the implicit hierarchy in the complete network.

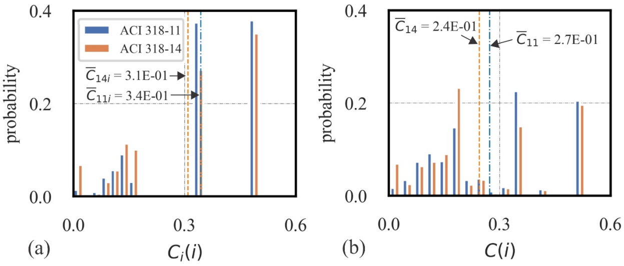


Figure 8. Clustering coefficient probability distributions for (a) implicit (C_i) and (b) complete (*C*) networks.

While the clustering coefficient indicates the prevalence of connected 3-node subgraphs in the network, motif analysis is used to identify *overexpressed* connection patterns in directed subgraphs of 3 or more nodes. Under-expressed subgraphs, compared to random, are also identified but are not considered motifs. For three node subgraphs, 13 non-isomorphic variations exist as shown along the horizontal axis in Figure 9. Each ID can be parsed to its unique adjacency matrix. Adding a fourth node increases the number of possible variations to 199 while 5 and 6 node subgraphs have 9364 and 1,530,843 variations, respectively [37].

Motif detection of subgraphs with 3, 4, and 5 nodes was performed for ACI 318-11 and ACI 318-14 implicit and complete networks using the open-source software mFinder (v1.2) [38]. The frequencies of individual subgraphs in a real network are determined to have statistical significance by comparing these to the subgraph frequencies found in a number (n = 1000 used here) of randomly generated synthetic networks created using the configuration model, which preserves the real network's joint degree sequence [39]. That is, the synthetic networks preserve nodal in and out-degrees and reconnect the nodes randomly via edge switching. Motif identification criteria included a z-score greater than 2, with p-value less than 0.010, and at least 4 occurrences not sharing nodes (uniqueness). z-score indicates the magnitude of deviation of the subgraph concentration found in real networks compared to the synthetic networks.

A summary of results of the motif analysis is presented in Table 2, while detailed results can be found in Rogers [30]. The variety of motifs with greater than 3 nodes occurring in the complete ACI 318-11 reference network is substantially greater than those occurring in ACI 318-14. This disparity exists only between the complete networks, indicating explicit references may be employed more discriminately in ACI 318-14. ID38 is fundamental to the network definition adopted here, while IDs 98, 102, 110, and 238 all represent cyclic referencing, as seen in the schematic representations shown in Figure 9. Identifying and eliminating unnecessary motifs may improve the consistency of the standard and, in-turn, the user experience.

Table 2. Motifs found across ACI 318-11 [26] and ACI 318-14[27].

		ACI 318-11 Implicit	**ACI 318-11 Complete**	**ACI 318-14 Implicit**	**ACI 318-14 Complete**
sub-graph size	**3**	38	38, 46, 98, 102, 108, 110	38	38, 46, 98, 102, 108, 110
	4	78, 92, 344, 394, 472	67 motifs[a]	78, 92, 344, 394, 472	40 motifs[a]
	5	24 motifs[a]	462 motifs[a]	24 motifs[a]	307 motifs[a]

[a] reported in Rogers [30]

End-users report that circular references are challenging to manage and authors identify them as areas of conflict within a standard [21]. Cyclic subgraph structures in a standard may be challenging for users to confidently resolve. These structures may be necessary; for example, if the provisions are closely related semantically and require an iterative design process. The concentration of cyclic subgraphs of size 3 decreased from ACI 318-11 to ACI 318-14. Figure 9 shows that both standards share similar expression patterns. Although they did not meet the motif criteria in either network, IDs 98, 102, and 110 occur in concentrations 1.2, 2.6, and 2.6 times greater, respectively, in ACI 318-11 than in ACI 318-14. That is, the networks over- and under-express the same subgraphs, though each to a different extent. ACI 318-14 complete and implicit networks express subgraphs of size 3 more extremely (relative to the average of the synthetic models; concentrations do not always track) than their ACI 318-11 counterparts in almost all cases, indicating a refined structure.

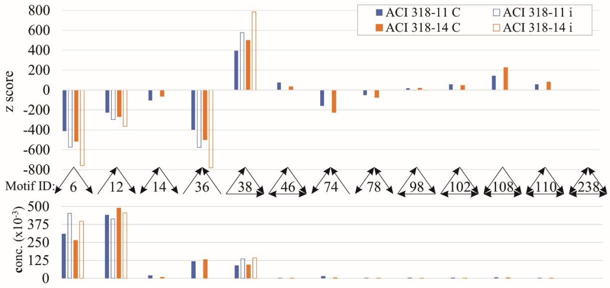


Figure 9. ACI 318 motif z-scores and concentrations found in implicit and complete networks for 13 possible subgraphs with 3 nodes (shown schematically along horizontal axis).

5.3 Grouping nodes by connectivity

Large clusters of nodes can be identified based on their connectivity to each other using the Girvan-Newman algorithm [40]. Heuristically, clustering aims to maximize inter-group edges and minimize intra-group edges. The Girvan-Newman algorithm successively removes edges bridging groups from the original graph until the modularity score (Equation 7) is maximized. The Girvan-Newman modularity score is the difference between a community's actual edge density and the expected number of edges if connected at random within the network [41]. Edge importance was measured by edge betweenness centrality scores (Equation 8) in each sub-network for each iteration of the algorithm.

The modularity score of a partition of a network, Q_c, is:

$$Q_c = \frac{1}{2m}\sum_{i\neq j}\left(A_{ij} - \frac{k_i k_j}{2m}\right)\delta_{ij} \qquad (7)$$

where: **A** is the adjacency matrix of the network (defined with respect to Equation 1);

k_i is the total-degree of node i;

m is the number of edges; and,

δ_{ij} is the Kronecker delta function; i.e. $\delta_{ij} = 1$ if $i = j$ and $\delta_{ij} = 0$ otherwise.

Edge betweenness centrality, $C_b(e)$, of an edge e is the sum of the fraction of all pairs of geodesic paths that pass through the edge:

$$C_b(e) = \sum_{st}\frac{n_{st}^{e}}{g_{st}} \qquad (8)$$

where: g_{st} is the total number of geodesic paths from s to t;

n^e_{st} is the number of those paths passing through edge e; and,

$n^e_{st}/g_{st} = 0$ if $g_{st} = 0$, by convention.

Modularity score maximization assumes communities within a network are statistically similar (assortative), results here found them to be only slightly assortative. The modularity score was maximized at 33 partitions for both ACI 318-11 and ACI 318-14. Many nodes that share a parent chapter tend to cluster together, though some more strongly than others. One shortcoming of this clustering approach is that it generates clusters of approximately equal sizes. Because chapters are not uniformly sized and their edge distributions are not statistically consistent, smaller clusters [chapters] group together and are absorbed into larger clusters more easily. Closely examining the clusters, some provisions demonstrate strong affinity outside of their designated chapter clusters, indicating a stronger structural relation to the clusters found here.

Cramer's V statistic can be used to measure association between nominal variables and is comparable across datasets with different scales (numbers of independent variables) [42]. Ranging from 0 to 1, Cramer's V indicates whether categorical frequencies are independent ($V = 0$) or perfectly associated ($V = 1$):

$$V = \sqrt{\frac{\chi^2/n}{\min\left(c-1, r-1\right)}} \tag{9}$$

If discrete variables P (i = 1, ..., r) and Q (j = 1, ..., c) are given by frequency,

n is the number of observations;

c is the number of columns;

r is the number of rows; and,

χ^2 is the Pearson chi-squared statistic, given as:

$$\chi^2 = \sum_{i,j} \frac{\left(n_{ij} - \frac{n_{i.}n_{.j}}{n}\right)^2}{\frac{n_{i.}n_{.j}}{n}} \tag{10}$$

where n_{ij} is the number of observations at (P_i, Q_j);

$n_{i.}$ is the number of times the value P_i is observed; and,

$n_{.j}$ is the number of times the value Q_j is observed.

For the clusters identified using the Girvan-Newman algorithm, Cramer's V (Equation 9) for ACI 318-11 and ACI 318-14 are 0.791 and 0.746, respectively. Both results indicate moderate association between chapters and the clusters found by the Girvan-Newman algorithm, meaning that one provides information about the other. It is fair to say that ACI 318-11 clusters into the prescribed chapters more favorably than ACI 318-14, which is likely due to the ACI 318-14 toolbox chapter format which creates many inter-chapter links.

5.4 Geodesic path analysis

The geodesic (shortest) paths between all pairs of provisions in each of the explicit, implicit, and complete reference networks were found using the Floyd-Warshall algorithm [43]. The geodesic paths are visualized here using heatmaps – shown in Figures 10 and 11 – in which each geodesic path between all pairs of provisions is represented by a pixel shaded to represent the path length. In these heatmaps, the vertical axis datum is the 'source' provision and the horizontal axis datum is the 'target' provision of a path. Because the network is directed, the plots are not symmetric about the main diagonal. The plots show paths that project both forward (above main diagonal) and backward (below main diagonal) from each provision.

The implicit reference networks connect only in the 'forward' direction. The explicit reference networks reach both forward and backward, but are sparsely populated (so much so that a figure is not informative – these are presented in Rogers [30]). The explicit network is not connected, therefore paths are typically shorter (but much less numerous) than in their implicit counterparts. 59% of nodes in ACI 318-11 are active in the explicit network, compared to only 51% in ACI 318-14 (Table 1). Reflecting the explicit forward to backward ratio reported Table 1, ACI 318-11 (ratio = 0.80) has more activity below the main diagonal than above and also has more activity below the main diagonal than does ACI 318-14 (ratio = 1.31). The volume of backward references has a disproportionate impact on the connectivity of the complete network and is believed to be disruptive to the 'natural forward flow' of the standard.

The complete reference networks exhibit traits from their constituent networks, but also emergent properties. By inspection, moving vertically through the complete network heatmaps, ACI 318-11 (Figure 10) appears more homogeneous than ACI 318-14 (Figure 11), indicating specialized chapters and a modular hierarchy in the latter. For instance, grey horizontal 'bands' in these figures, broken only near the main diagonal (e.g., last half of chapter 10 in Figure 10 and more frequently in Figure 11) indicate that the provisions do not have outgoing references and are likely reachable only along the implicit path. It is possible that some of these can be reached by direct references, which are represented by individual pixels that are very hard to see in these figures. However, those direct references would have to occur deep within subsections (i.e., to specific requirements, rather than to a broad chapter or section), otherwise a vertical streak through the grey bands would be apparent. Examining paths out of ACI 318-14 Chapter 6 in (rectangular callout in upper right of heatmap shown in Figure 11), a short path to a specific clause in Chapter 19 is seen. The reference must occur late in Chapter 6, because the dark vertical streak extends the entirety of outgoing Chapter 6, meaning all of Chapter 6 before the reference can also reach Chapter 19 along a relatively short path (i.e. "quickly"). The target reference must be a specific subsection in Chapter 19 because only a small portion of incoming Chapter 19 is banded horizontally. Examining the reference itself confirms this:

"6.6.4.4.3 *The effective length factor* k *shall be calculated using* E_c *in accordance with* ***19.2.2*** *and* I *in accordance with* ***6.6.3.1.1****. For nonsway members,* k *shall be permitted to be taken as 1.0, and for sway members,* k *shall be at least 1.0."* [27]

Inspecting the heatmaps horizontally, ACI 318-11 relies heavily on references to previous provisions in the document (as seen by the darker regions below the main diagonal in Figure 10). A notable exception is Chapter 5 *Concrete Quality, Mixing, and Placement*, which requires a longer path to return to than other chapters, indicated by the faint vertical bar. Counterintuitively, paths backwards to provisions in ACI 318-11 are often shorter than those directed forward in the standard. ACI 318-14 more heavily favors forward references, particularly to the material and toolbox Chapters 19-25 (this is expected), with Chapter 5 *Loads* and Chapter 6 *Structural Analysis*, both over-riding topics, being exceptions. Excluding Chapter 16, the typical references to Chapters 5 and 6 occur in subsection 4 *Required Strength* of each source "structural member” chapter. The following example is circled (left side of heatmap) in Figure 11:

*“**11.4**—Required strength*

***11.4.1** General*

***11.4.1.1** Required strength shall be calculated in accordance with the factored load combinations in **Chapter 5**.*

***11.4.1.2** Required strength shall be calculated in accordance with the analysis procedures in **Chapter 6**. …*” [27]

The need for these provisions is debatable, particularly from the standpoint of minimizing the number of provisions, since in most cases they are not providing exceptions to the rule of utilizing Chapters 5 and 6 for load determination and analysis, respectively, which is established implicitly. However, such provisions likely serve as important waypoints for novice end-users and provide a structure and rhythm to the standard via their consistent location in each chapter. One could also argue for relocating Chapters 5 and 6 to the toolbox chapters, since they are essentially used in the same manner. The counter argument is that these placements are intuitive since they follow the typical design process (requiring load determination and analysis prior to member design), which may be the most consistent mental map shared by users of the standard.

Also seen in Figure 11 are (dark) bands representing short backward paths within Chapter 18 (diamond-shaped callout), one of only a few hotspots below the main diagonal in ACI 318-14’s heatmap. This unique pattern may indicate that the arrangement of this chapter is suboptimal and could be redrafted more efficiently to maximize the implicit forward path.

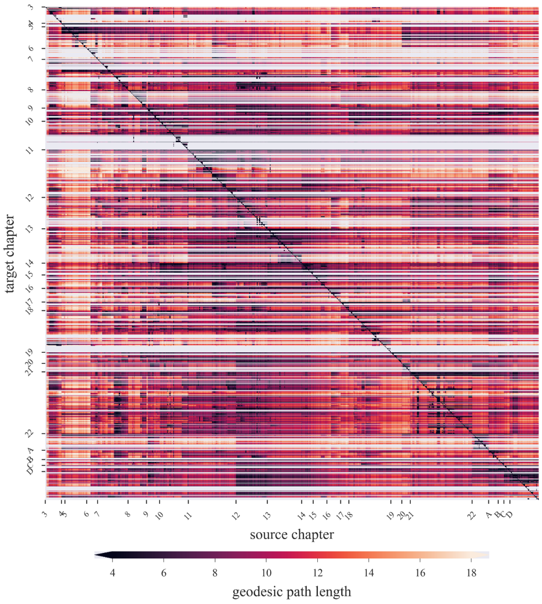


Figure 10. ACI 318-11 [26] complete network all pairs geodesic path lengths.

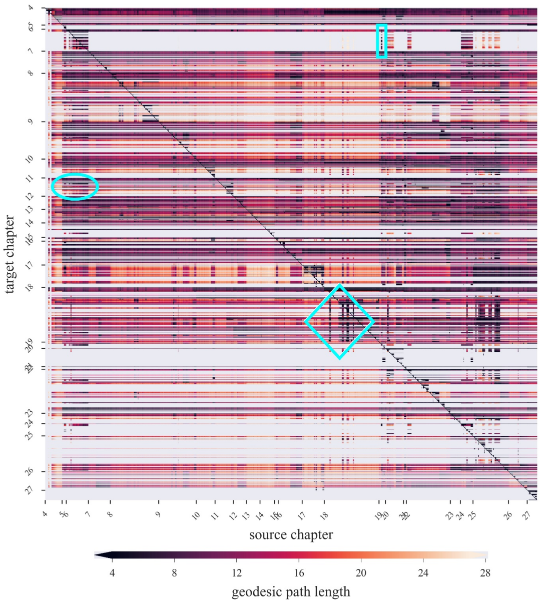


Figure 11. ACI 318-14 [27] complete network all pairs geodesic path lengths (boxed regions described in text).

5.4.1 Geodesic path distributions

Distributions of the geodesic path lengths for all provisions in the complete reference networks are shown in Figure 12. The curves representing the cumulative count ***for each bin*** were tested for best fit against common distributions and found to be well represented by a normal distribution in both cases. ACI 318-14 is more heavily skewed to longer geodesic path lengths, likely indicative of nodes with specialized connectivity.

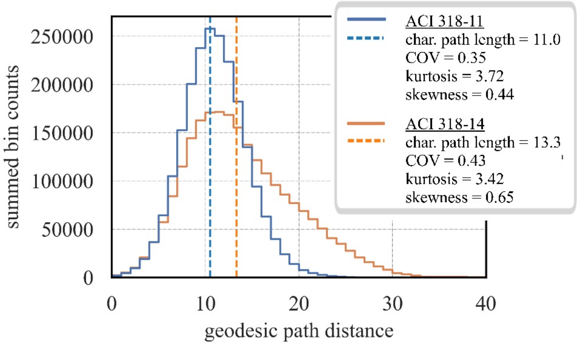


Figure 12. Geodesic path length distributions summed across all pairs.

6 Discussion

For the first time, network representations of a standard with nearly identical content before (ACI 318-11 [26]) and after (ACI 318-14 [27]) a significant (and reportedly successful) reorganization were developed and analyzed to better understand the relationship between the structure and navigational complexity of design standards. The network analysis techniques demonstrated in this study can be applied to existing and proposed standards to measure their topological features. The interpretation of those features will vary based on the standard’s size, scope, maturity, governing body, and how that standard is used in practice. A holistic understanding of the standard being considered is necessary; there is no single metric that will always signal a relatively less complex standard. The discussion of topological features is presented here in as general a manner as possible. Nonetheless, the present discussion is influenced by the context of ACI 318; a mature North American concrete design standard featuring side-by-side commentary.

The authors contend that topological features are useful for standard writers or their critics to consider when debating the quality of standard's structure, potential reorganization, or the placement of new provisions. Based on user feedback, fundamental network characteristics are better indicators of navigational complexity than the number of pages or provisions, which is often cited by critics of a standard's increasing complexity. Fundamental network characteristics shown in Table 1 are useful bases for comparisons between standards as they are simple to obtain from the network model and predictive of many of the conclusions drawn from more in-depth analysis. SWB should design network structures that maximize indicators associated with positive user experience, such as the ratio of forward to backward explicit references, and minimize negative features such as strongly connected component fractions as these are most likely to enhance ease-of-use and reduce complexity. The limitations of these indicators however are unknown; some back-referencing or strong connectivity is likely necessary to a well-functioning standard.

Early in the standard-writing or revision process, centrality and geodesic paths should be examined in order to provide insight into atypical reference structures and reference concentrations. Several provision groups with high centrality scores in ACI 318-11 were extensively revised in ACI 318-14 (Figure 6). This information can be used to substantiate the need for reorganization or revision of specific groups of provisions in a candidate standard. Moreover, the efficacy of the revision to improve user experience may be measured by the reduction of high centrality groupings. SWB should consider mean closeness centrality to better understand the effects of explicit references on the network and therefore the health of the implicit network, by proxy. That is to say, between two versions of the same standard having different structures, the difference between the complete and implicit networks' mean closeness centrality scores will likely be less in the better organized version of the standard. An SWB should not depend on the explicit network to compensate for a poor implicit structure. Once again, limitations of this indicator are yet to be tested.

The most useful tool developed in this research is likely the geodesic path length heatmaps (Figures 10 and 11). The general flow of the standard, clustering trends, homogeneity, hotspots, and specialized chapters can all be inferred from visual inspection of geodesic path length heatmaps. This novel application of heatmaps is particularly useful because the entire reference network can be easily visualized with higher tractable information density than cluster maps (Figure 6, for instance). That is to say that accurate conclusions on the way the network behaves on both local and global scales can be quickly assessed by visual inspection, without intensive interpretation. This approach allows for reorganization or revision targeted to less efficient sections of a standard document. Like many of the other analyses presented, this information can also be used as part of a body of evidence towards improving the draft of a design standard.

Standards can be improved by measuring motifs with the intent of limiting cyclic and atypical reference structures. Users' confidence that all provisions related to a design instance have been satisfied is likely to increase if the user is generally directed forwards in a standard with minimal disruption and is provided a natural stopping point (i.e. the user encounters typical motifs and few cyclic motifs). Fenves [21] reported improving standards by reducing circular references. Motif analysis in this study found lower concentrations of cyclic subgraphs in ACI 318 following the 2014 revision. With modern computing power, these and other less-understood motifs can be relatively easily investigated. Cyclic subgraphs with 4 or more nodes were not explicitly investigated although the variety of motifs with 4 or more nodes occurring in the complete ACI 318-11 reference network is greater than those occurring in ACI 318-14 (Table 2). Further research into identifying and eliminating unnecessary motifs (and their functions) could improve the consistency of the standard and the user experience.

7 Conclusions

Contrary to existing practice, this study proposes that network analysis is a useful and accessible tool for standards-writing bodies (SWB) to manage navigational complexity, particularly if paired with a mechanism to gain user feedback. Network analysis, as described in this paper, can be made increasingly available through the ubiquity of so-called artificial intelligence tools [30]. The tools described provide an opportunity for building standards addressing nonconventional and emerging materials and technologies to avoid some of the pitfalls of increasing complexity. This is believed to be especially important for standards whose stakeholders are less homogenous and have more diverse expertise and experience – such as building standards aimed at regions in the Global South.

In the most general terms of network understanding, the case study reorganization of ACI 318-11 [26] to ACI 318-14 [27] demonstrates that user experience can be improved by (1) aligning the implicit network more closely with the end-users' mental map of the design space; (2) maintaining a consistent structure with recognizable motifs and minimal explicit references; and, (3) creating a deep, modular hierarchy. A variety of network analysis techniques were demonstrated to have a capacity to: (1) provide evidence that a standard can be made more efficient by being reorganized; (2) identify specific areas within a standard affecting utility; (3) identify the better of multiple alternatives; and, (4) measure the efficacy of an intervention.

7.1 Future needs

The limitations and applicability of many of the indicators of complexity identified in this study are unknown and can only be made known through studies on a broader population of standards.

Although paper and paper-facsimile (PDF) based standards dominate the construction industry today, a transition towards digital web-based media is likely (and has begun in some instances). The issue of structure, however, will not be alleviated by this transition. The structure of a standard reflects the relationships between the requirements of the standard. In fact, understanding these relationships may become more important in providing a smooth transition to digital since users will expect easier navigation from a digital format. The models presented here are relatively coarse, with nodes representing entire provisions. Much may be gained by increasing the granularity to investigate datum within the provisions.

The importance of understanding the intended user of a standard cannot be overstated. Design standards exist to serve many objectives, but none are achievable if the standard cannot be properly decoded by the user. Commentary acts as a parallel communication channel from the SWB to the end-user and its presence or absence inevitably influences the content of the mandatory portions of the standard. This effect was not studied here but should be investigated in the future.

Data availability statement

The datasets generated and/or analyzed in the current study are available in the University of Pittsburgh Institutional repository D-Scholarship (http://d-scholarship.pitt.edu/44251/) and reported in their entirety in [30].

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