Structures of Building Design Standards: Leveraging Network Analysis to Understand Perceived Complexity

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Building and construction design standards can be challenging for users to efficiently navigate. The construction industry relies on standards to reduce uncertainty between stakeholders. Nascent industries (e.g., bamboo, FRP, earthen construction) can be stifled by overly complex standards, whose redevelopment cycles are often sporadic and resource intensive. Navigation through a standard is considered to play a key role in the user experience. This study explores the complexity of building design standards from the perspective of users and investigates network analysis as a tool for identifying and ultimately mitigating navigational complexity.

A survey of users of the American Concrete Institute's (ACI) structural concrete design standard, ACI 318, found that traits of standards deemed most important by respondents were also perceived as having been improved in the extensive structural revision of ACI 318 carried out between the 2011 and 2014 editions. ACI's stated aim was to enhance ease-of-use via alignment of the layout (structure) of the standard with the typical design workflow. The revision included only minimal changes to technical content, providing a measure of control in this study.

In this study, ACI 318-11 and ACI 318-14 were abstracted as networks composed of provisions (nodes) and references (edges). Networks were extracted from their respective texts using natural language processing techniques and enriched with semantic embeddings to investigate the relationship between structural features and 'meaning'. Network characterization revealed several network features associated with positive and negative user experiences. Results suggest that the hierarchical structure of a design standard should mirror the mental map of the design space held by users to facilitate forward flow and efficient location of necessary provisions for a design instance.

Based on these results, a case study was conducted on the developing International Organization for Standardization (ISO) structural bamboo design standard, ISO 22156:2021. This study establishes a baseline and provides suggestions to mitigate user-perceived navigation-related complexity in the next version of ISO 22156.

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I consider this dissertation one of two of my greatest personal achievements so far, the other being military service. As a Marine, I was challenged physically but all questions had an answer; every 'mission' had an objective. As a researcher, I was challenged by ambiguity: questions are ill-posed, results are interpretable, and most positions are defendable. Unexpectedly, I found it immensely challenging to trust myself in this new role. In addition to those mentioned above, my family and friends always fed me confidence. Thank y'all for not letting me forget that above all I'm a Louisiana swamp-person.

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Glossary

Due to the nature of this work, a Glossary of terms is provided. Terms indicated with ⸸ in the text are defined in this glossary.

Throughout this dissertation, the generic term “standard” is used to describe consensus documents that include test methods, practices, specifications⸸, or requirements written in mandatory language⸸ with the intent of being adopted by authorities having jurisdiction⸸ (AHJ) to govern building design and construction practices.

assortative mixing – tendency of nodes with similar properties to share edges within a network (Newman 2010).

authorities having jurisdiction (AHJ) – all agencies, individually or collectively, with legal jurisdiction to adopt, administer, and/or enforce the requirements of building regulations.

building codes – sets of requirements enacted as law and enforced by the AHJ controlling various aspects of building design, construction, and/or occupancy. In United States’ practice, a model building code becomes the legally enforceable building code when enacted.

centrality – a measure that quantifies how important vertices (or edges) are in a networked system (Newman 2010)

characteristic path – the mean geodesic path length in a network (Newman 2010)

configuration model – a random graph constructed with a given degree sequence (Newman 2010).

connected graph – an undirected graph in which paths exist between all nodes (Newman 2010).

consensus – general agreement, characterized by the absence of sustained opposition to substantial issues by any important part of the concerned interests (i.e. stakeholders) and by a process that involves seeking to consider the views of all parties concerned and to reconcile any conflicting arguments (ISO/IEC Guide 2:2004).

customer attribute (CA) – Customer needs or attributes that the customer desires (Suh 2001).

decoupled – independence of FRs can be guaranteed if and only if the DPs are determined in a proper sequence (Suh 2001).

degree – the number of edges connected to a node. Can be directed ‘in' to a target node or ‘out’ from a source node.

design parameter (DP) – ‘the key variables in the physical domain that characterize the design that satisfies the specified FRs’ (Suh 2001).

diameter – the length of the longest existing geodesic path between any pair of nodes in a network (Newman 2010).

directed graph – a network where each edge has a direction, pointing from a source to target node (Newman 2010).

disassortative mixing – tendency of nodes with dissimilar properties to share edges within a network (Newman 2010).

embedding – a dense vector representation of the meaning of a word or group of words (Mikolov et al. 2013).

function requirement (FR) – Function Requirements (FRs) are a minimum set of independent requirements that completely characterizes the functional needs of the product (or software, organizations, systems, etc.) in the functional domain. By definition, each FR is independent of every other FR at the time the FRs are established (Suh 2001).

geodesic path – the shortest path between two nodes in a network (Newman 2010).

guide – a normative document using permissive language that is meant provide guidance, instruction, or best practices.

independence axiom – “maintain the independence of the functional requirements (FRs)” (Suh 2001).

information axiom – “minimize the information content of the design” (Suh 2001).

joint degree sequence – the list of in and out-degree for each node in a graph.

mandatory language – language in standards or specifications imposing requirements or obligation. Often characterized by words such as ‘shall’, ‘must’, ‘will’, etc.

model building code – a set of requirements for buildings that is developed and maintained by an SWB. When enacted by the AHJ, this becomes the legally enforceable building code.

natural language model – a human language model that assigns probabilities to sequences of words.

path – a series of nodes connected by edges.

permissive language – language in guides and other normative documents denoting a right or option. Often characterized by words such as ‘may’, ‘should’, ‘can’, etc.

process variable (PV) – the key variables in the process domain that characterize the process that can generate the specified DPs (Suh 2001).

random graph – a network model which possesses a given network property but is otherwise random (Newman 2010).

reference network – a graph constructed where nodes represent provisions and edges represent references between provisions.

regulation – document providing binding legislative rules, that is adopted by an authority.

scale-free network – a network whose degree distribution follows a power law (Newman 2010).

severability – in law, referring to a provision which states that if some of the terms of a standard are found to be unenforceable, the remainder should still apply. For example, ACI 318-14 Clause 1.5.7 reads:

> *In any case in which one or more provisions of this Code are declared by a court or tribunal to be invalid, that ruling shall not affect the validity of the remaining provisions of this Code, which are severable. The ruling of a court or tribunal shall be effective only in that court’s jurisdiction, and shall not affect the content or interpretation of this Code in other jurisdictions.*

specification – concise statements of requirements for materials, products or services.

standard – a document established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context (ISO/IEC Guide 2:2004). A building code is one type of standard.

standard writing body (SWB) – a committee of delegates of a standard writing organization responsible for developing a particular standard.

strongly connected graph – a directed graph or subgraph in which a path exists between all nodes (Newman 2010).

uncoupled – each of the FRs can be satisfied independently by means of one DP (Suh 2001).

weakly connected graph – a directed graph or subgraph in which a path exists between all nodes if paths can go in either direction along an edge (Newman 2010).

zigzagging – process of decomposing FRs and DPs in the functional and physical domains to create the FR and DP hierarchies. (Suh 2001)

Abbreviations

AASHTO – American Association of State Highway and Transportation Officials
ACCC – automated code compliance checking
ACD – allowable capacity design
ACI – American Concrete Institute
AEC – architecture engineering and construction
AHJ – authority having jurisdiction
AISC – American Institute of Steel Construction
ANSI – American National Standards Institute
API – application programming interface
ASCE – American Society of Civil Engineers
ASD – allowable stress design
ATC – Applied Technology Council
AWC – American Wood Council
BERT – Bidirectional Encoder Representations from Transformers
BIM – building information modeling
BS – British Standards
CA – customer attribute
CBOW – continuous bag of words
COV – coefficient of variance
DLT – decision logic tables
DP – design parameter
DSM – design structure matrix
EC – Eurocode
FOL – first order logic
FR – function requirement
FRP – fiber reinforced polymer
HITS – Hyperlink-Induced Topic Search

GPT – Generative Pre-Trained [model]
GN – Girvan-Newman
IBC – International Building Code
ID – identification
IEC – International Electrotechnical Commission
IEEE – the Institute of Electrical and Electronics Engineers
INBAR – International Network for Bamboo and Rattan
IRC – International Residential Code
ISO – International Organization for Standardization
LFRD – load factor resistance design
NA – network analysis
NBCC – National Building Code of Canada
NBS – National Bureau of Standardization
NLP – natural language processing
NOCMAT – non-conventional and vernacular materials and technologies
NSS – not statically significant
OED – Oxford English Dictionary
OWL – Web Ontology Language
PCA – principal component analysis
PDF – Portable Document format
PE – Professional Engineer
PSF – partial safety factor
PV – process variable
regex – regular expressions
SASE – Standards Analysis Synthesis and Expression
SDO – standard-development organization
SEI – the Structural Engineering Institute
SWB – standard writing body
UBC – Uniform Building Code
UX – user experience

1.0 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 documents[†] or construction documents[†], or otherwise required by an authority having jurisdiction (AHJ), provide an important basis for trust between project stakeholders, including owners, designers, occupants, regulators and, ultimately, the public at large. 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 (AEC) believe the value and usefulness of standards are being undermined by a steady rise in their complexity (Thompson 1947; Galambos 1992; Searer 2006; Searer et al. 2007; Hess 2009; DeFriez 2014a, 2014b; Searer and Rosenboom 2014; Pierson 2016; McClean 2018). Others maintain standards have inherent complexity due to their purpose and the nature of their content (Bulleit 2012, Nethercot 2012). End users often point to ‘ratcheting’ in which the documents’ size, number of provisions, references to additional standards, or their reliance on supporting documentation increases, as evidence that a standard is less functional than in previous editions. Many end-users experience standards as complex, but “a clear and consistent definition of complexity is not found throughout the literature” (Bucciarelli 1996).

Standard-writing bodies[†] (SWB), who are themselves end users, must continue to encode in standards the ever-growing body of building design knowledge. The individuals comprising SWB, are also end users who are most often volunteering their time and other resources.

Additionally, 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

(ASCE 2020). Furthermore, standards must evolve to accommodate new demands and objectives, requiring protections from new or more frequent and extreme hazards associated with climate change, for instance (ASCE 2022). Efficiently developing new standards for novel materials or methods as they emerge to address some of these challenges is also required. However, very few tools are available to aid authors and SWB in evaluating or improving their documents. The structure of the standard document is critical to the user experience yet very little research has been conducted on how to implement a document structure that allows for growth and expansion while minimizing complexity.

1.1 Objective and Scope of Research

The objectives of this research are to develop the language and tools to help SWB improve the structure of construction and building standards – and therefore their utility – by (i) better understanding users' needs and experiences when using a standard, (ii) synthesizing and correlating those needs with reference network[†] features in the standard, and (iii) creating actionable guidance to improve the structure of standards.

Objectives (i) and (ii) are addressed considering a range of national and international building industry standards. ACI 318 *Building Code Requirements for Structural Concrete and Commentary* serves as a 'case study'. Taking the lessons learned from (i) and (ii), objective (iii) will be 'demonstrated' using ISO 22156:2021 *Bamboo – Structural Design*, a new design standard focusing on a nonconventional material. These case studies were selected based on availability of source material and subject matter expertise.

This research focuses on standards associated with the structural design of buildings. “Building” and standards associated with buildings and construction are understood to refer primarily to structures conventionally addressed by the *International Building Code* or *International Residential Code*. The nature of standards across construction-related disciplines (plumbing, electrical, environmental, fire, etc.) or other structural types (bridges, nuclear facilities, etc.) are similar and the concepts described may be extended with appropriate subject-matter expertise. Standards having similar objectives are found across engineering disciplines. Although this study is focused in two structural design standards, the methods described and recommendations are believed relevant across the spectra of engineering standards.

2.0 Structural Design Standards for Buildings

2.1 Standards and Codes

The term ‘standard’ broadly refers to the conventions that specify or control engineering practice. Contemporary standardization largely began in the crafting industries with stamped markings on metals to indicate the material’s purity. Today, nearly all aspects of engineering practice are governed by standards dictating performance or prescribed criteria for materials, components, and systems. Standards also prescribe the various design, documentation, communication, manufacturing, quality assurance, and other processes necessary to create an artifact or product. Standards may be developed internally at corporations or firms, by manufacturers, trade organizations, or national and international SWB. Standards may be adopted voluntarily or required from contract or regulation. Thompson (2021) summarizes: “virtually every aspect of engineering practice is circumscribed by tests that certify compliance with prior criteria for devices and processes of a given type”. At a high level, standards serve to increase efficiencies, interoperability, trade, and consumer satisfaction.

In structural engineering practice, engineers predominately operate with design standards and their associated specification[†] and testing standards. Specification and testing standards typically specify demonstrable characteristics of the material or artifact, such that end-users of the standard can ensure compliance with criteria. Design standards typically specify rational and acceptable methodologies for the design, analysis, and verification of an artifact as well as establishing constraints and minimum requirements. Design standards are limited in scope by the material type (concrete, steel, timber, etc.) and the structural application (buildings, bridges, tank, special structures, etc.). The common building design standards in the United States are created and maintained by professionals composing standard-writing bodies internal to technical associations (such as: American Concrete Institute, American Institute of Steel Construction, American Wood Council, American Society of Civil Engineers, American Association of State Highway and Transportation Officials, etc.).

Design standards in civil construction are unique to those in other heavily standardized industries, such as the automotive or aerospace manufacturing, primarily because civil construction standards are used for design verification rather than full-scale prototype compliance testing (Angelino et al. 2014). In other words, a structural design standard should ensure that all standard-compliant designs are also structurally adequate designs – without knowing what the actual design will be, or indeed, overly restricting the design. Standards are established by consensus[†]: their content has been debated and agreed upon by consensus in committees formed and regulated by SWB who require (or at least strive for) proportional representation of manufacturers, practitioners, users, and general interest stakeholders. Due to the nature of the construction industry, the general interest category is often dominated by academics but also usually includes enforcement officials. Because of the need for consensus among the SWB, structural design standards tend to be a conservative representation of the body of knowledge in the structural engineering domain; they represent the state-of-practice not necessarily the state-of-art in civil engineering (Harries et al. 2020). Knowledge from prior experiences is encoded into standards, establishing rational limitations for design based on understood (or agreed upon) fundamental principles, subassembly and material properties, environmental variables, etc. Of course, not every situation a designer faces will be explicitly addressed by a standard. Bucciarelli (1996) argues that the nature of design is ahistorical, while the nature of standards is historical and therefore standards can “never assure the successful and safe performance of the artifact or system in all of its ways”. It follows that standards and their SWB must be flexible and forward-looking. Nonetheless, excellent structural design standards alone are not enough to ensure performance or safety. They must also be situated within social and/or regulatory environments which enforce ethical behavior and - above all - competency.

In civil engineering, mitigating risk from hazards is a primary interest of most stakeholders, particularly with respect to fire and structural integrity. Many standards that set requirements for safety become legally mandated by the AHJ. Model building codes[†] are a set of building and material standards that can adopted by designers, owners, investors, or other stakeholders through inclusion in construction documents[†]. A model standard or code becomes mandatory when adopted by an AHJ as the minimum legal safety and quality requirements for the design, construction, and occupation of buildings or other related infrastructure. Mandatory, or legally binding, rules are known as building regulations. In the United States, the dominant model building codes are those promulgated by the International Codes Council which include the *International Building Code* (IBC) and *International Residential Code* (IRC). In many cases, these are amended before being adopted by the AHJ, typically a state or municipal government[1].

Building codes often include language that permits the regulated entity to demonstrate equivalence with a portion of the code, theoretically giving the entity freedom to innovate beyond the scope of the standard. However, in practice the explicit and prescriptive regulatory requirements require less competence to meet, are much easier for enforcement officials to verify, and are economic solutions for common situations. For better or worse, these circumstances have

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[1] In the absence of an adopted state or local building code, CFR 24 578.75 mandates the adoption of the IRC or IBC for all projects under federal Housing and Urban Development (HUD) jurisdiction, for instance.

led to the pervasive ‘design by code’ paradigm in which designers may be code-knowledgeable but understand less of the underlying mechanical principles.

Building standards serve an important role in protecting public health and well-being, facilitating contracts and trade, improving quality and reliability of buildings, and reducing costs among others (Greulich and Jawad 2018). Because of this, the number and variety of stakeholders may be immense. Bredillet (2003) considers standards, when interpreted as socio-technical constructions, to be the product “of negotiations that enable complexity, ambiguity and uncertainty to be reduced within project stakeholder groups”. Based on this interpretation, a primary function of standards is to reduce uncertainty between stakeholders, particularly if one holds the position that ‘ambiguity’ and ‘complexity’ are analogous to uncertainty. When evaluating the impact of their content to produce the best outcomes for the widest breadth of stakeholders, building standards should almost always be considered in context of the socio-technical systems (Figure 2.1) in which they are deeply rooted (Leveson 2004, Meacham and van Straalen 2018, Angelino 2019). The scope of this dissertation excludes a critical analysis of any standard’s specific content, or the manner in which it impacts the broader socio-technical ecosystem. Instead, we focus on gleaning insight from the *structure* of individual standards as they expand and contract to accommodate new information while still serving the primary purpose of delivering knowledge to users in a logical and useful way.

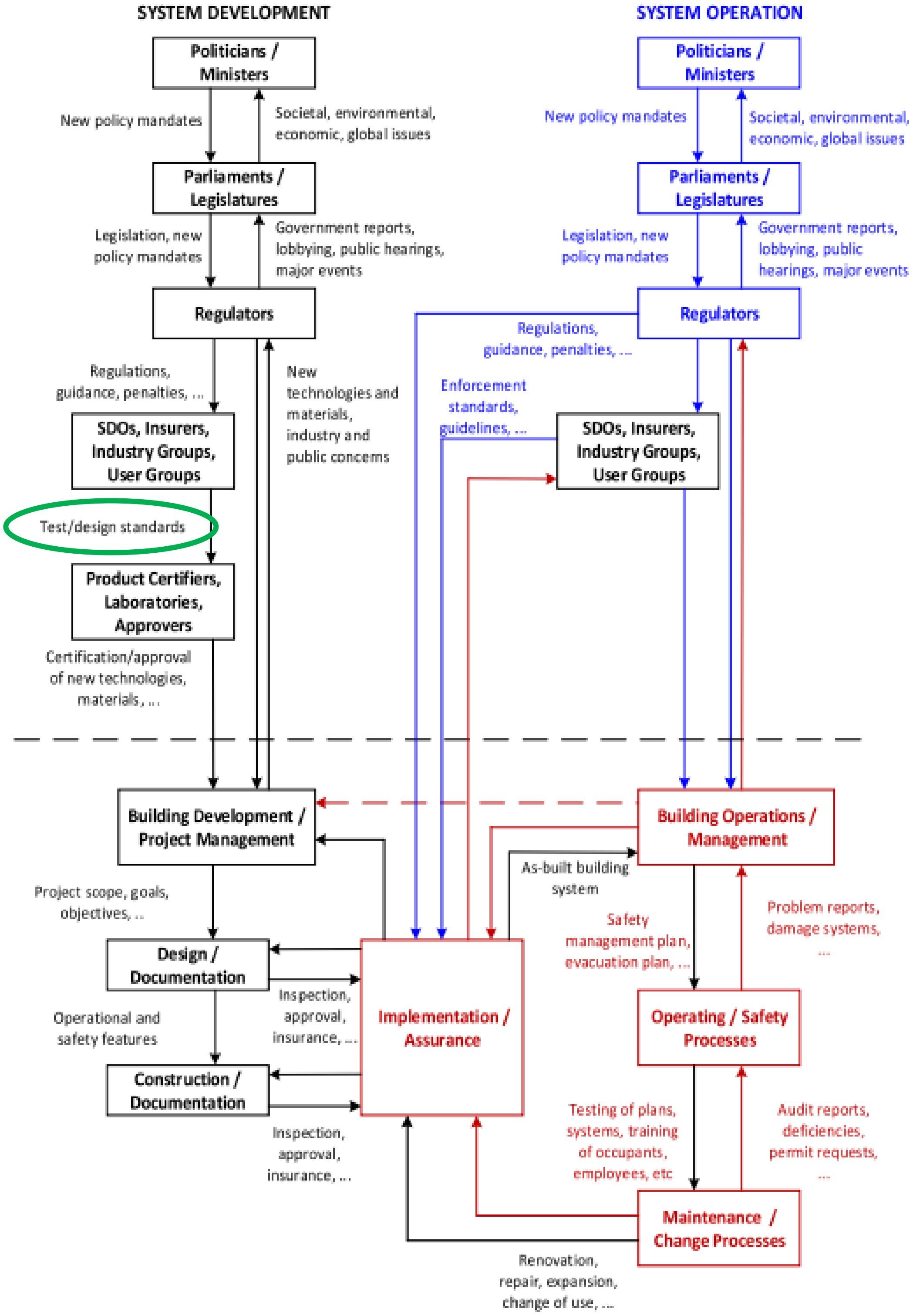

Figure 2.1 Model of the socio-technical regulatory system in which standards exist (circled) adapted from Meacham et al. (2020). In this figure, SDO (standard-development organization) is the same as SWB used in this dissertation.

An individual design standard can be thought of as a system of knowledge (1) encoded by SWB, (2) communicated via some medium, then (3) decoded by end-users who (ideally) arrive at similar, reasonable interpretations (Bulleit 2012). At each of these steps and among most of their sub-processes, the probability that the intended knowledge is properly decoded and absorbed by the end-user marginally decreases. That is, these processes may increase uncertainty in the system achieving its required function. The original intent of the authors of a standard, analogous to a communication signal, can be lost if the channel becomes too noisy (i.e., too uncertain). Uncertainty held by competent designers in achieving compliance with a standard is a failure of the standard itself (Poston 2009). The semantic presentation of a standard is critical since ambiguous words or phrases can dramatically increase uncertainty, leaving room for interpretation or manipulation. The structure of a standard, i.e., the hierarchically organized layout of sections and provisions and their various relationships within and out of the standard, can also cause confusion for the end-user and lead to misinterpretation, unsatisfied requirements, and potentially unsafe designs (Nyman et al. 1973, Galambos 1992, Greulich and Jawad 2018).

2.1.1 Standards for Novel Technology

Standards serve as important *lingua franca* for materials and methods in the AEC industry. They allow disparate stakeholders to share information within a common frame of reference and more reliably determine material and system behaviors (Zhang and El-Gohary 2016, Harries et al. 2020). This is particularly true in standards for non-conventional and vernacular materials and technologies (NOCMAT; the example returned to in this dissertation will be bamboo structures). NOCMAT typically do not have large professional organizations or industry-accumulated knowledge, and often rely more on a body of artisans and tradespeople with a wealth of inherited knowledge. The interest in NOCMAT, and its increasing penetration into the AEC community, is driven by complex combinations of environmental concern associated with conventional construction, population increase and continued urban migration, among other socio-economic factors. A feature of NOCMAT is that it is largely being led by, and is perhaps more relevant to, developing regions with fewer resources for standards development. A significant benefit of building standards is that their very existence can spur local economic growth in impoverished areas when trusted (and adopted) by industry professionals (Xue and Zhang 2018). The economic impact of the existence of standards is reportedly greater than that of patents and professional licensure (Swann 2010).

Natural structural materials such as earth and bamboo have historically been marginalized often due to negative social perceptions (Ben-Alon and Koko 2020), low profitability, or technological limitation. Similarly, novel or innovative engineered materials, such as fiber-reinforced polymer composites (FRP), are often perceived as niche markets and may be marginalized, albeit for different reasons. Champions of NOCMAT have struggled to find room for growth next to the dominant materials of the construction industry: timber, concrete, and steel. In recent decades, however, it has become more common for designers and owners to consider a lifecycle approach to design, many times including and prioritizing additional consideration for "sustainability" credentials such as embodied energy or carbon. NOCMAT, broadly defined, often address this change in values.

Paraphrasing the so-called Bruntland report, in order to promote sustainability AEC must find ways to provide safe housing and other infrastructure to meet the needs of the world's poor and developing nations without sacrificing the abilities of future generations to meet those same needs (World Commission 1987). Industry practices are evolving quickly as many conventional materials and practices will not meet these increasingly prevalent demands for sustainability. Many NOCMAT (e.g., strawbale insulation, adobe bricks and structural bamboo) sequester carbon, have low-embodied energy, have potential to develop local economies, and even improve mental health and wellbeing (Ben-Alon et al. 2019). The speed at which the benefits of NOCMAT, which are essentially adaptations to changing requirements in AEC, can be manifest is throttled by regulation and industry trust, which depend on having functional codes and standards.

2.1.2 Challenges in Developing Standards for Novel Technologies

Regulations must be sufficiently robust to minimize risk to stakeholders while being flexible enough to permit innovation for novel materials, systems, and practices. This tension, and tensions between stakeholders, manifest in standards in a variety of [perceived] 'trade-offs': safety vs economy, simplicity vs comprehensiveness, and performance vs prescription, to name only a few. Decisions are made that may prefer one stakeholder, reducing the quality and increasing the complexity for another stakeholder. One common such tension is the adoption of performance standards, that experienced designers prefer, versus prescriptive standards, that code enforcement officials can more easily verify. 'Deemed to satisfy[†]' requirements are a compromise in this case but are not always possible. 'Performance' versus 'prescriptive' may in fact be a false dichotomy presented to users, that may be more accurately described as 'outcomes' versus 'methods'-based requirements (or 'ends' and 'means'). The difference is subtle but allows a more nuanced understanding of standards. Requirements typically specify (or define) to a satisfactory outcome or a methodology for a achieving a satisfactory outcome. Rarely is the performance of a design actually verified or components explicitly prescribed. Considering three types of requirements, each regulating one of the three design spaces (function, physical, and process in 2.3.3), may help to further refine our understanding of requirements.

Novel material or technology (which includes NOCMAT) standards under development also suffer from the chicken or egg paradox, since a critical mass of design/construction/manufacturing experience and invested manpower are needed to establish a standard, yet that body of knowledge depends on reliable and agreed-to standards of practice before widespread adoption and in-depth research can be conducted (Mottram 2017). In emerging fields, SWB must craft a document that is functional based on limited information and stakeholder input with few of the resources that may be available to those writing standards in more conventional or established fields. Critical mass theory has been used to describe similar phenomena among users creating wikis in Wikipedia, an analogous knowledge sharing community (Prasarnphanich and Wagner 2011). Communities, and by extension their standards and industries are in a precarious position during this early stage. The new standard could harm the industry if it is perceived as too complex or places stakeholders at a disadvantage (Angelino et al. 2014, Harries et al. 2020, World Bank Group 2015, Coglianese 2016). As early versions of standards are ‘incomplete’, SWB need tools to ensure that their documents can evolve as new knowledge is gathered through research and practice. Useful stakeholder input from outside the authoring committee is limited in the early life of a standard (some argue throughout the standard’s life (Nethercot 2012)), writers also need to better understand how their documents will be perceived by end-users to ensure valuable resources are not wasted in the critical early stages of development.

Exploring the general research into user experiences, at least two concepts related to complexity are informative in the context of developing standards, especially for novel materials: Tessler’s Law of the Conservation of Complexity and the Poka-Yoke Principle. Tessler’s Law states that there is some minimum amount of complexity in a system or process that must be accommodated either by the designers of the system or the end users (Yablonski, 2020). It follows that in most cases a goal for designers should be to eliminate any unnecessary complexity for the users, thereby making the service easy and intuitive. This can be thought of as simplification of the rules or actions required by the end-user. A balance must be struck between a complicated process, where a great deal of information is presented or expected of the user, and a simplified process where the user must interpret high-level abstractions, i.e. first principles.

The Poka-Yoke Principle was developed by Shigeo Shingo in 1961 at Toyota and is a means of reducing complexity by constraining the user's options (Saffer, 2010). Adhering to the Poka-Yoke Principle ensures that proper conditions exist before a process begins, which should prevent problems occurring during the process. Examples of this concept applied in building design standards are constraints placed on material and geometric properties in design, minimum qualifications of the designer, providing explicit process steps to the user, or limiting the applications of a simplified procedure.

2.2 Complexity in Building Standards

Researchers and end-users can easily draw the conclusion that growing complexity in standards is likely to cause more errors, leading to potentially unsafe designs. Defining what makes one standard document more complex than another is more challenging. Many point to an increase in the size of the document (sometimes called ratcheting) as direct evidence of complexity, usually referencing the increasing number of pages, provisions, or references (e.g., Bulleit 2012; DeFriez 2014a, 2014b; Hess 2009; McLean 2017, McLean and Huston 2018). While physical features of the document may indicate complexity, defining complexity in the physical domain does not provide a clear and consistent means to improve the document. Surely, within rational limits, a large and detailed design standard that is well-organized can perform as well or better than a small standard that is poorly organized and provides only general information.

2.2.1 Anecdotal Understanding of Complexity in Standards

Anecdotal evidence gathered from literature reviews of trade publications and debates recorded during major British Standards (BS) and Eurocode (EC) revisions suggest complexity has been a growing problem in building codes for some time (Angelino 2019). As Nethercot (2016) states:

> *"Codes of practice are an 'easy target' for complaint by structure engineers. 'Too complex', 'does not cover what is needed', 'too expensive', 'difficult to follow', 'poorly organised', 'not needed' are the sort of comments overheard frequently in conversation, read in the correspondence columns of Engineering Journals and Magazines and offered during discussion sessions at meetings and courses."*

Selected quotes from end-users regarding complexity in the North American building code context include:

> *"…codes are too complicated and too difficult to use…"* (Searer 2006).
>
> *"…overly complicated…[taking up] substantial shelf space"* (Hess 2009 describing the 'Building Code').
>
> *"[The] ACI* [318] *Building Code has become a compendium of lengthy equations and intricate problems of logic."* (Fling 1979).
>
> *"The* [ACI 318] *Code is very complex for average building designers to understand.* [The] *code is very wordy. Formulas could be used in place of many textual descriptions. The Code is updated too often. We cannot keep up with the changes."* (Poston 2009).
>
> *"Another potential problem with the continued growth in the size of building codes is that the number of provisions may, in a way, overload the communication channel."* (Bulleit 2012).

Munshi (2006) provides a more nuanced evaluation:

> *"...the perception that the* [ACI 318] *code is becoming too complex stems from four underlying factors: a knowledge gap exists between code writers and practitioners, the language used in the provisions is not readily interpreted, the volume of the document is continually increasing, and the organization of the provisions is convoluted."* (Munshi 2006).

Neither is the issue of complexity a new complaint. Woolson, writing in 1925, on behalf of the Building Code Committee[2] of the United States Bureau of Standards, states:

> *"The committee has received numerous complaints that existing building codes leave much to be desired in clarity and convenience of reference.... Some codes are very brief, omitting whole chapters of important building regulations entirely, and treating others so inadequately as to leave much doubt of their meaning. Other ordinances are unnecessarily verbose. ...The arrangement of subjects and their subdivisions seldom follows the same order except when one code is practically a verbatim copy of another. Sections on administration frequently are scattered throughout the body of the ordinance, leaving the prospective builder uncertain whether he has complied with all the preliminaries. Requirements stated in one chapter are found considerably modified in another, and without a cross reference to protect the user of the ordinance from error. Matters not even distantly related to each other are treated in the same sections. Complementary provisions, on the other hand, are often separated by several pages or chapters. To add to the confusion most codes are inadequately indexed, and some not at all."*

Ambiguity in building standards is a common theme:

> *"All building codes have poorly worded provisions that are unnecessarily complex, are ambiguous, are not justifiable, or are overly restrictive."* (Searer 2006)

> *"...1997 UBC, the 2000 IBC, or ASCE 7-05 do not agree on whether the example structures are redundant or reliable, leading one to conclude that perhaps none of the formulations are meaningful."* (Searer 2006)

> *"Wind speed, a term commonly understood even by nonengineers, has now been transformed into a set of contrived velocities that have no intuitive or actual relationship with how hard the wind actually blows....ASCE tells us up-front that you will get different results* [from different code-prescribed approaches to wind design]. *Is that supposed to give us confidence?"* (DeFriez 2014a referring to ASCE 7)

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[2] This Committee is now ASCE 7.

> *"Is every new edition of the Code an improvement over the last one, or does it react to a problem…by requiring additional calculations or design constraints that likely add cost to the project, do not always address the real cause of failure and can sometimes result in a detrimental effect?…some of the revisions may have been required to correct "advancements" in previous editions that did not recognize how those provisions would be interpreted by practicing designers and contractors, or what provisions of other codes or standards would be brought into conflict."* (Hess 2009)

Approaches for potential improvement of building codes are described and limitations identified.

As Poston (2009) reports:

> *"The lack of adaptability of the* [ACI 318] *Code to changing technologies and methodologies was the subject of repeated discussion ... What became clear is that there is a lack of formal roadmap on how new items and concepts are addressed within the structure of the Code. Each new item or concept introduced requires adjustment and fine-tuning across numerous existing provisions. With the best intentions, the net result of decades of change over several Code cycles, and hundreds of individual decisions result in a document that is* ***less than fully synchronized****. This suggests that an improved organizational structure of the Code would enhance the future ability to add new material into the Code in a logical location that the end user would intuitively know where to look."* [emphasis added].

As Fling (1979) makes a similar argument three decades earlier:

> *"…There is a distinction between how to simplify the* [ACI 318] *Code itself and how to simplify the use of the Code as it stands. The former is a difficult task and cannot be accomplished by individual action. The latter is much easier."*

Fling argues that incremental improvements to the standard intended to provide more efficient (i.e., less conservative) designs and/or slight to no economic advantage are typically not worth the additional effort of implementing in design. Notably, Fling doesn't argue against improving the standard; he argues against designing by the standard in typical situations. Other pitfalls of implementation are also noted:

> *"The important question is what can be done constructively to ameliorate the situation within known limits of legal principles, technical knowledge, and administrative competency.... It calls also for sympathetic understanding of the fact that many problems which appear at first glance to be relatively simple prove, when analyzed, to resemble the vitamin B complex in that they turn out to be an assortment of items each of which has to be recognized and evaluated."* (Thompson 1943)

> *"Codes that are too complicated (often overly explicit) make it difficult for a designer to know how many and which of the requirements must be met to justify a specific design. Therefore, although explicit* [prescriptive] *requirements may at first make for better encoding, using a large number of explicit requirements that are strongly interconnected will make the decoding process more difficult."* (Bulleit 2012)

> *"Currently, in most countries around the world, prescriptive codes are used as the primary means of fire safety design. Many of these codes have become complex and unduly restrictive because of the constant imposing of new requirements in addition to the existing ones."* (Hadjisophocleous and Benichou 1999)

Ultimately, DeFriez (2014a) phrases the issue of complexity in an existential manner:

> *"…It is the unreasonable and unnecessary degree of complexity in building code provisions and design methodologies that poses the greatest danger to the future vitality and survival of our profession."*

In the context of complexity in engineering systems in general, Leveson (2004) summarizes:

> *"We are designing systems with potential interactions among the components that cannot be thoroughly planned, understood, anticipated, or guarded against. The operation of some systems is so complex that it defies the understanding of all but a few experts, and sometimes even they have incomplete information about its potential behavior. …The problem is that we are attempting to build systems that are beyond our ability to intellectually manage: Increased interactive complexity and coupling make it difficult for the designers to consider all the potential system states or for operators to handle all normal and abnormal situations and disturbances safely and effectively."*

In the introduction to his 1967 textbook *Structural Analysis*, Brown, rather tongue in cheek, claims structural engineering to be:

> *"The art of molding materials we do not really understand into shapes we cannot really analyze, so as to withstand forces we cannot really assess, in such a way that the public does not really expect."*

In their own way, both Leveson and Brown highlight the primary paradox of building standards.

2.2.2 Formal Definition of Complexity in Standards

Although it is clear that many end-users are frustrated with the state of modern design standards, a standard definition of complexity in standards is not clear in the literature. Fuzzy themes from the literature include:

- Uncertainty induced by poor or inconsistent phrasing or document structure, incongruent cross-references, and inadequate commentary.
- Transitions from one paradigm to another (ASD to LFRD, new wind design provisions, new material specifications). ‘Complexity’ *appears* to decrease with time but increase with alterations.
- Justification is disproportionate for additions as opposed to retractions.
- Judgement is shifted from designers to authors, denying the individual’s experience and discretion or turning engineers into analysts and technicians. In some ways, responsibility is also shifted away from designers as they increasingly ‘design to code’.

Identifying an operational definition of complexity is the logical first step in addressing complexity. Based on the commonly accepted meaning of complexity reported in the Oxford English Dictionary (OED 2022), complexity appears built into the system due to its many parts and the degree of uncertainty arising from interactions between the parts:

> *“**Complex** - Consisting of parts or elements not simply coordinated, but some of them involved in various degrees of subordination; complicated, involved, intricate; not easily analyzed or disentangled.*”

There are three readily apparent ways to reduce complexity using this definition; reduce the number of parts, reduce the entanglement between them, or make the entanglements easy to understand. However, this definition is ambiguous as to what is ‘simply coordinated’ or ‘easily analyzed or disentangled', yet it is absolute in the sense that the artifact is either complex or it is not complex – there is no way to compare alternatives. While admittedly the OED definition captures the essence of complexity in standards, this definition does not lend itself to a systematic means of reducing complexity in any system. The following sections identify an operational definition adopted from systems design literature.

2.3 Axiomatic Design

Suh (2005a), during his development of axiomatic design and its associated theory of complexity, also found that defining complexity is insufficient to reduce it. The underlying themes of uncertainty found in the literature (Section 2.2) give support for the adoption of Suh's definition of complexity in the context of the present research: "*Complexity is ... a measure of uncertainty in achieving the specified FRs* [Function Requirements]" (Suh 2005b).

This definition is general, flexible, and allows for comparison of alternatives, yet it is not easily implemented or adopted without controversy. This definition makes a critical distinction between complicatedness and complexity, calling for a shift in thinking away from the physical expressions of complexity towards the ability of the engineered system to meet its functional (performance) requirements[†] (FRs). Structural engineers may be familiar with this line of thought given the prevalence of performance-based design and reliability engineering in the field. Engineers are inclined to describe a design that meets all performance requirements as being of high-quality (De Weck et al. 2011). A high-quality design may be complicated (composed of many pieces) and may be the product of a complex design process (e.g., trial and error) or a simple prescriptive process. By any approach, however, uncertainty has been reduced such that the final artifact confidently performs as intended and required. When a design is uncertain to meet intended performance requirements, engineers may be inclined to call this design complex. The design may be complex because the performance requirements are ill-defined, challenging to meet or measure, or may change over time.

Considering a building design standard, performance must be defined in relation to the needs of various stakeholders. The primary stakeholders of interest in this dissertation are the designers, inspectors, educators, researchers, material producers, builders, forensic investigators, and facility managers, collectively referred to as ‘end-users’ of the standard. Notable stakeholders not directly considered here as end-users are owners, the public, financiers, insurers, lawyers, government interests, or tangential corporate interests. The primary concern is understanding how end-users of the standard perceive complexity in utilizing a standard in practice and identifying means of quantifying and limiting that complexity to only that which is necessary. The tangential stakeholders conventionally have no interaction with the standard itself.

Axiomatic design, inspired by the Taguchi method, is a formal framework of design based on fundamental principles or axioms common across nearly all design problems, namely the Independence and Information Axioms. It can be thought of as providing quantitative criteria to discern good and poor design decisions but requires a clear formulation of the design objectives through function requirements and constraints (Suh 2005a). A concise overview of axiomatic design, including reference to various applications, is provided by Brown (2020). This dissertation is not an extension or even an application of axiomatic design (although I argue for application of such a methodical approach to designing design standards in the future), but rather uses it as a framework to understand the amorphous concept of complexity.

2.3.1 Complexity in Axiomatic Design

According to axiomatic design principles, complexity takes two primary forms independent of time: real and imaginary. Real complexity is the difference between the intended performance (design range) and the actual performance (system range) (see Figure 2.2). Real complexity exists because the artifact or system does not always satisfy all FRs. The system must be modified: either the FR and/or a design parameter[⸸] (DP) must be modified to reduce real complexity. Reducing real complexity in a system requires reducing the information content of a design, also known as the uncertainty, in accordance with the information axiom[⸸]. The obvious correspondences in a paper standard are modifying DPs to eliminate redundant provisions, eliminate ambiguous phrases, reduce the number of steps in a required task, etc. Challenges will present themselves when one DP is used to satisfy more than one FR, because altering the DP to optimize one FR may adversely affect others. Consider deleting a duplicate provision in a standard to decrease ‘repetitiveness’ and improve ‘portability’ and ‘ease of navigation’; an unintended consequence may be a standard that feels ‘inconsistent’ to the user who must now deviate from their active path through the standard to the location of the retained provision. This may influence other qualities, or customer attributes[⸸] (CA), of a standard important to the user such as ‘speed of application’, ‘centralization’, and ‘independence’ (further discussion of such qualities can be found in Section 2.3.3). These interactions between FRs are called coupling in the system, which can be mitigated by establishing FRs and DPs in accordance with the independence axiom[⸸]. Decoupling[⸸] (sequencing couples) and uncoupling[⸸] (eliminating couples) FRs allows for selecting DPs that minimize information in the design. Coupled designs are likely to have more real complexity than decoupled or uncoupled[⸸] designs for the same set of FRs. It should be noted that reducing coupling is not always possible. An example of a very high-level DP coupling many FRs is the use of a paper medium or digital paper facsimile to communicate the standard. Modern digital representations such as ACI 318 PLUS[3] or ASCE 7 Online[4] and the ASCE 7 Hazard Tool[5], will reduce complexity ‘simply’ by removing or reducing many of the user-apparent interactions between FR.

Real complexity can also be time-dependent, when the system or design ranges shift due to new FR (i.e., inclusion of sustainable practices in addition to minimum safety requirements or pushing the envelope with innovative/optimized structures). Many SWB publish on a periodic cycle, largely addressing this type of complexity. Parameters outside the design of the artifact or system that affect its performance, such as the drafting, voting, and consensus processes are called process variables[†] (PVs) in axiomatic design theory. These are largely outside the scope of this dissertation, although the conclusions drawn are intended to be of use to SWB engaged in these processes.

The second type of complexity, imaginary complexity, exists due to a lack of understanding of the system design or its behavior. To illustrate, Suh (2005a) asks his reader to consider a combination lock: opening the lock without knowing the passcode is a complex task since most attempts will end in failure. But if we know the code, the task is trivial. Similarly, imaginary complexity is the complexity new standard users experience during the familiarization period; the standard can produce quality designs, but the user may not interpret it correctly. Experienced users understand the sequence that must be followed to use the standard, while new users (or experienced users with a novel problem) may struggle and require a “guide” to assist them in navigating the document to satisfy various requirements. This may also partially explain why experienced users

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[3] subscription-only interactive digital version of ACI 318.
[4] subscription-only interactive digital version of ASCE 7
[5] https://asce7hazardtool.online/

often perceive changes to a standard as increasing complexity. Just because the complexity is ‘imaginary’ does not mean that is not a concern for the designer. Commentary, guides[†], and a thoughtful user interface (i.e., providing the passcodes for the lock) can reduce the perception of complexity for end-users.

2.3.2 An Example Case: Legibility and Font Size

> *“The best size for a building code is, of course, a matter of personal opinion, but it is generally conceded that it should be such as to be easily carried in a coat pocket.”* (Woolson, 1925 writing, on behalf of the Building Code Committee[6])

To illustrate the concept of complexity based on function and to help define the terminology of analysis, an intentionally simplistic example is presented:

The main body (excluding appendices) of ANSI A58.1-1982 *Minimum Design Loads for Buildings and Other Structures*, is 16 pages. In 1988, this standard was revised and redesignated ANSI/ASCE 7-88; the revision was 40 pages (for the record ASCE 7-22 is 396 pages excluding appendices). If complexity were defined by page count, a physical characteristic, ASCE 7-88 would be more complex than ANSI 58.1-82. However, upon inspection it is found that the most significant factor contributing to the expanded page count is that the font size was increased in 1988, possibly as an attempt to improve legibility.

Taking this example to extremes [although considering the Woolson quotation, above, perhaps not unreasonably so], at some small font size the standard becomes illegible and unusable

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[6] This Committee is now ASCE 7.

for some percentage of the population of end-users. Assuming this was not the intention of the designers, then we can consider this percentage equivalent to the complexity of the design in satisfying the legibility (or accessibility) FR. If the font size is further reduced, the standard will eventually become unusable to all users. The same can be said for increasing the font size. Therefore, there must exist some probability density function that relates legibility, a desired CA of the document, to font size, a DP. An appropriate font size could be determined from user experience surveys or from existing data on accessibility. Other DPs of a standard must also influence legibility, such as contrast, font type, and line spacing. A CA desired by the end-user can be translated into one or more FRs when described technically so that it is actionable or measurable. For the CA “legible”, the designer might specify the FR to be “legible in office lighting conditions for 95% of the population.”

Multiple FRs describing portability or document navigation may also be dependent on the DPs used to satisfy legibility; these FRs are therefore coupled with legibility (and each other), meaning one FR cannot be improved without affecting another FR. Considering portability, a change in font or spacing may increase page count beyond a functional level (for example, the loose-leaf version of the *AASHTO LRFD Bridge Design Specification* (2020) runs to 1912 pages using a base font size of 10 pt). FRs are coupled by (1) the DP we chose to satisfy them and (2) how the designer defines them. Uncoupling FRs will theoretically always result in design improvements, by allowing an individual DP to be modified to optimize an FR without adversely affecting another.

To the first point, one can assess choosing a digital medium instead of paper document to satisfy the ‘legibility’ FR without affecting portability or document navigation FRs – satisfying the Independence Axiom. To the second point, one could argue that the ‘legibility’ FR could be further decomposed into FR for contrast, font size, line spacing, etc. all of which could be instantly modified in a digital medium – satisfying the Information Axiom by allowing the user to ‘choose’ DP that maximize their success at satisfying FR.

The ASCE-7 font size example demonstrates that (1) complexity cannot necessarily be measured directly by DPs or physical expressions of a standard, but instead should be measured in the function domain by asking how well the DP satisfy the FR; and (2) FRs that share DPs may interact such that one cannot be improved without adversely affecting the other. Considering complexity from a functional perspective, it can be quantified as the difference between the design range of a FR and the actual system’s performance probability density function, visually represented as the shaded area in Figure 2.2. If a potential DP for the system increases the probability that the independent FR is satisfied, then it reduces complexity and increases quality: the DP is desirable for the document and quality management schemes can be implemented to assure this DP is selected.

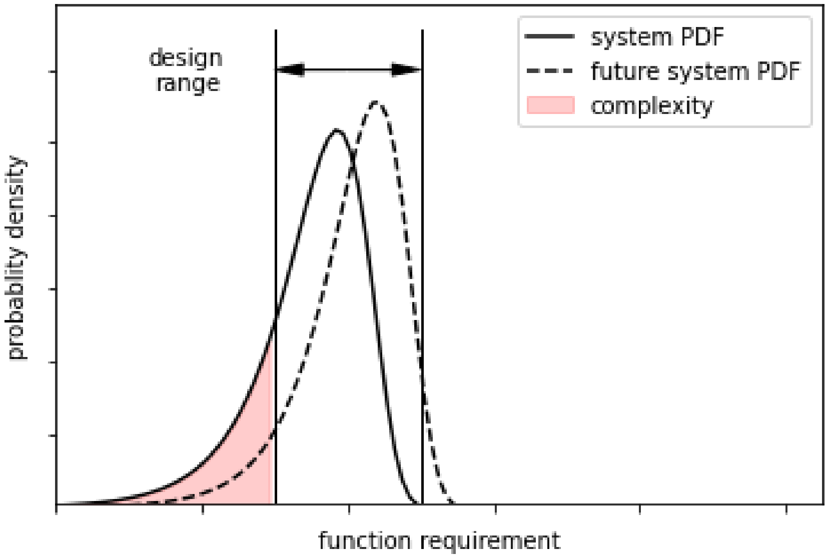


Figure 2.2 Visual representation of complexity (shaded), adapted from Suh (2005b). Complexity is performance-dependent and often time-dependent. The probability that the system functions outside the design range for a given FR is quantified complexity. The design range consists of an expected value and some tolerance. The performance of most mechanical systems will degrade as they age (for example), which results in (often) worse performance and a shifting probability density function. The direction of the shift, much like the shape of the probability density function, depends on how the FR is defined (e.g. error rate vs success rate). Systems that don't physically degrade will also display a shifting probability density function as outside pressures exert new demands and constraints on the system. Flexibility and cyclic revisions can address time-dependent real complexity.

2.3.3 Performance Requirements and Indicators of a Standard

Researchers have described a variety of CA for standard documents (Harris and Wright 1981, Fenves 1987, Galambos 1992, Janssen 2000, May 2003, Sherif et al. 2007, Bulleit and Adams 2011, World Bank Group 2015, Greulich and Jawad 2018), although none as comprehensively as Angelino (2019). Fenves (1987) identified a loose set of holistic CAs for standard documents as he developed the Standards Analysis Synthesis and Expression (SASE) methodology. He reports that the structure of the standard should be 'complete' and 'clear', the provisions need to be ‘unique’, ‘complete’, and ‘correct’ with their relations ‘connected’, ‘acyclic’, and ‘consistent’. Generally, the CAs found in Fenves (1987) and earlier works by Harris and Wright (1981) can be thought of as guiding principles “for standard writers, by standard writers”. Nonetheless, no systematic research to identify CAs of standards from other perspectives was apparently undertaken by these authors at that time.

Arlani and Rakhra (1988) identified top-level CAs of the National Building Code of Canada (NBCC 1985), constructed a design structure matrix (DSM) of interactions between them, and also noted technical, economic, and social performance measures that could be utilized to measure quality. Few researchers go so far as to decompose higher-level functions into sub-functions and their design parameters or investigate the interactions between requirements. DSM is a tool developed in operations research to identify interactions in complex systems or processes. Here ‘top-level’ CAs are those applicable to the entire standard, not just a section or provision. Suh (2005a) provides a related methodology to decompose the hierarchy of CAs, FRs, DPs, and PVs (Figure 2.3). Decomposing the top hierarchies may be practical but requires expert knowledge and insight into the user experience. The accuracy of the process on a socio-technical system such as a building standard document would be challenging to verify for all stakeholders.

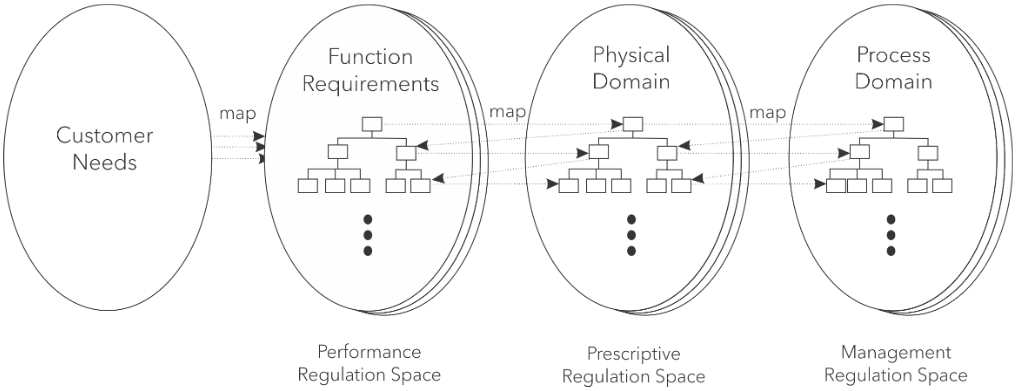


Figure 2.3 Design space abstracted in axiomatic design theory adapted from Suh (2005a). From left to right: Customer needs are mapped to independent high-level FRs, physical DPs are selected that best satisfy the FRs and constraints, and finally PVs are selected in the process domain to create or enact DPs. After making a selection in the domain forward, we can move down the hierarchy to make deeper selections in a process known as zigzagging[†]. Each domain has its own regulation space associated with it, indicating the hierarchy of potential regulatory interventions in the design process.

In a return to systems thinking, and in an effort to directly study complexity, Angelino et al. (2014) conducted interviews with stakeholders and reviewed public debates and other literature to identify 31 top-level CA (referred to as Quality Dimensions by Angelino) of a building standard; in this case the Structural Eurocodes (summarized in Table 2.1). Angelino (2019) used surveys based on those findings to investigate and develop best practices to improve Highways England's *Design Manual of Road Bridges* (2018). These same CAs are expected to be representative of established North American structural design standards and their stakeholders, although extending this assumption to stakeholders in other geographical regions or to NOCMAT is likely to be inappropriate.

Table 2.1 Key quality dimensions of design standards and their definitions
adapted from Angelino et al. (2014)

Quality Dimension	Definition	Potential Measurement Tool[a]
Accessibility	The extent to which technical provisions are easily and quickly identified within the same standard or, when cross-referenced, in other documents	DLT, NA
Accuracy	The extent to which technical provisions/clauses are correct and reliable	
Centralization	The extent to which technical provisions are concentrated in specific clauses of the standard or in a specific standard	DLT, NA
Clarity	The extent to which technical provisions are clear in scope, limitations, and language with minimized risk of misinterpretation and misapplication	NLP
Coherence	The extent to which technical provisions are presented in a coherent and logical way within the same standard and in cross-referenced standards	DLT
Completeness	The extent to which technical provisions are not missing and are sufficient for the design in hand	DLT
Comprehensiveness	The extent to which a specific clause includes all necessary information for the design in hand with no need to refer to other documents	NA
Conciseness	The extent to which technical provisions are succinctly written for the design in hand	NLP
Consistency	The extent to which technical provisions are presented in the same format (language and structure) in different parts of the same document or in other cross-referenced documents	NA, NLP
Cost-effectiveness (Constr.)	The extent to which technical provisions enable a cost-effective construction	
Cost-effectiveness (Design)	The extent to which technical provisions enable a cost-effective design	
Credibility	The extent to which design standards are trusted by target users	UX
Cross-referenced	The extent to which technical provisions are incorporated in the main text against the provisions contained in other referenced documents (annexes or external sources)	NA
Ease of navigation	The extent to which different technical provisions/clauses/standards are well connected and easy to follow	NA, DLT
Flexibility	The extent to which technical provisions are able to be applied/used easily for different design applications by users with different expertise	NA, UX
Know-how representation	The extent to which technical provisions enable users to understand how to satisfy technical requirements	UX
Know-what representation	The extent to which technical provisions enable users to understand what requirements are expected to be satisfied	UX
Know-why representation	The extent to which technical provisions enable users to understand the reasons behind those specific requirements	UX
Independence	The extent to which different technical provisions/clauses/standards are independent and changes do not affect other provisions/clauses/ standards	DLT
Integrability	The extent to which different technical provisions/clauses/standards are integrated with each other	DLT
Interpretability	The extent to which technical provisions are ambiguous and provide multiple interpretations from different users	DLT , NLP
Non-hierarchical integration	The extent to which different technical provisions/clauses are presented in non-hierarchical and organic way (no modularity, no ordered pattern in the structure)	NA
Repetitiousness	The extent to which technical provisions/clauses are repeated in different parts of the same standard or in other standards	NA, DLT
Relevance	The extent to which technical provisions are helpful for the design in hand	UX

Responsibility	The extent to which technical provisions clearly identify responsibility of different stakeholders	
Safety	The extent to which technical provisions lead to a sufficiently safe design	
Simplified	The extent to which technical provisions are presented in a fashion that can be easily applied by users without requiring an understanding of all the underlying principles	UX
Speed of application	The extent to which technical provisions can be quickly applied	UX
Up to date	The extent to which technical provisions are not outdated by advances in technology, understanding or practice	
Understandability	The extent to which technical provisions are easily comprehended by all target users with minimized risk of misinterpretation.	UX
Validity	The extent to which technical provisions are reliable thanks to appropriate research and sufficient practical experience	

[a] DLT = Decision Logic Tables; NLP = Natural Language Processing Methods; NA = Network Analysis,
UX = User Experience
Bold CA are those possible to address in this research.

It is not immediately clear how to measure some qualities or functions of a standard; this can be abstract and subjective. One approach may be the adoption of the concept of ‘requirements smells’ from software requirements engineering, where indicators of problematic textual requirements are identified and measured using features extracted from text using Natural Language Processing (NLP) techniques. Femmer et al. (2017) demonstrated automatic smell detection by identifying “bad” smells in several specifications and internal process documents from automotive, chemical, and software industries based on ISO/IEC/IEEE 15288 language criteria (indicators), admittedly with many false positives and an unknown number of misses. The result was a tool that highlights potentially problematic wording in text requirements, much like a spelling or grammar checker.

2.4 The Structure of a Standard

A building code and its referenced standards must be presented logically to avoid confusion and ensure that the end-user understands what is required of them and their design to meet code requirements efficiently (Geurlich and Jawad 2018). Logical arrangements unburden end-users, leading to a more egalitarian code that is more easily enforced. A single artifact in construction may be controlled by a variety of standards, while overall building performance may be controlled by an order of magnitude more standards. Systematic, logical and consistent arrangements across all of these documents (i.e., structural harmonization), makes it much easier for the end-user to ensure that they are fully compliant. These are not novel ideas. Woolson (1925) acknowledged all of these points and noted that the ad hoc and rapid expansion of American building codes would require a robust means of logical organization to maintain their usefulness. This was echoed by Poston (2009) in a summary of a surveys and workshops led by ACI to determine a path in their reorganization:

> *"What became clear is that there is a lack of formal roadmap on how new items and concepts are addressed within the structure of the Code. Each new item or concept introduced requires adjustment and fine-tuning across numerous existing provisions. With the best intentions, the net result of decades of change over several Code cycles, and hundreds of individual decisions result in a document that is less than fully synchronized. This suggests that an improved organizational structure of the Code would enhance the future ability to add new material into the Code in a logical location that the end user would intuitively know where to look."*

Through a process described as regulatory ratcheting, standards swell in size to accommodate new understanding (gained through research and practice), requirements (sustainability or equity, or natural hazards), technologies, or to address perceived problems in practice (Bardach and Kagan 1982). A well-known phenomenon is the challenge of removing or even altering provisions (or their organization) once they have been written into a standard, even if those provisions are ‘unnecessary’ or ‘ill-conceived’ (Bardach and Kagan 1982, Searer 2006, Searer et al. 2007). Standards-writing committees are often limited by resources and the bylaws of their controlling bodies in the number of ambitious changes that can be implemented in a revision. Large re-organizations are rare and should be implemented with care for future growth and the end-users’ experience in mind.

Standards are (typically) hierarchically composed of sections, subsections, and clauses each with progressively narrowing scope related to some building element, procedure, or behavior. Provisions can point, via references, to other provisions in the standard that must be satisfied, should be investigated by the end-user, or are related in some way. Some provisions will cite external standards. Design standards will often cite material specifications or testing standards. References can be explicit (i.e., naming the referenced provision or an external document) or implicit (sequential provisions or an input parameter or variable that is required from another provision). Figure 2.4 shows an example of internal explicit references for ISO 22156:2021. Although the purpose of references is not to guide an end-user through the document, *per se*, they are suspected to heavily influence navigation and the user experience.

If references to dependent or parent requirements are not present, end-users may be more likely to miss them. Alternatively, if all tangential requirements are referenced by a provision, the value of the references is lost, as a user must track down each during design. There may exist some optimal balance where necessary accompanied requirements are referenced while tangential provisions can be found naturally and nearby.

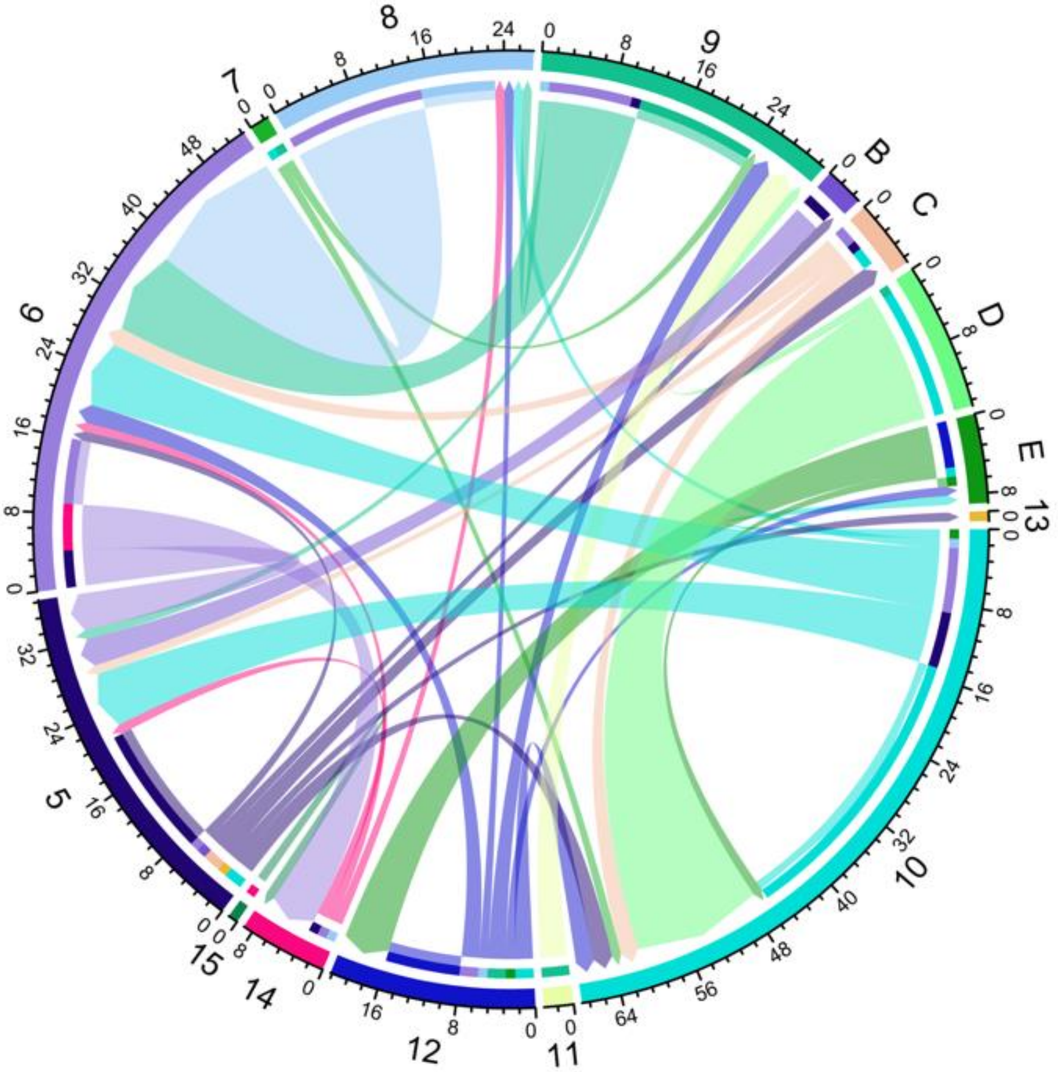


Figure 2.4 ISO-22156:2021 chord diagram. This diagram shows all of the explicit internal references between chapters within ISO-22156:2021. Arrows point from the source provision to the target provision (colors have no meaning and are simply provided for clarity). Counts with no arrows (blank peripheral blocks) represent self-references within the chapter. By inspection, chapters behave and relate in a variety of ways, e.g. Chapters 7 and 8 appear reliant on Chapter 6 which acts as a hub, interfacing with much of the rest of the document.

An intuitive structure can enable users to easily identify, locate, and interpret standard provisions for the job at hand, ensuring efficient use of resources, higher confidence in conformance, and greater user satisfaction with the standard (Frosch 2009). A poorly structured standard can cause confusion for the end-user and lead to misinterpretation, unsatisfied requirements, and potentially unsafe designs (Nyman et al. 1973, Galambos 1992). A familiarization period is usually necessary for new users, particularly for large standards with a broad scope. For established conventional technology, this process likely begins during undergraduate engineering education. In addition to the main sections for design and analysis, standard documents may contain informative appendices as well as supporting sections that define domain terminology. An integrated commentary or sanctioned independent guide may parallel the standard itself. In the engineering realm, textbooks often form a canon of ‘unofficial’ guides. Although this increases the material available to support design, these supporting resources are critical during the familiarization phase for new users (Bulleit 2012).

Moreover, the structure of a standard can cause confusion in the authoring phase with the SWB omitting requirements and creating logic errors or infinite loops. When comparing two versions with alternative structures, it is not clear which will better meet the needs of any of the multitude of stakeholders. Few methodologies or practical tools (beyond extensive ‘style guides’ that vary from SWB to SWB) have been developed to assist SWB to better structure a document. Modelling and analyzing the information and the relations that compose the structure of a standard have not been fully explored as a tool to improve a standard’s utility.

2.4.1 Representations of Building Standards

As discussed above, building standards formalize requirements and other information in a form that is convenient for designers and other stakeholders to use and reference. Paper and digital documents are media representations for this data, but are not the data itself, meaning standards can be represented in countless ways (Garrett et al. 2014). Hackitt (2018) recently called for investigating multiple representations of the performance requirements (and approved documents) in the UK building code based on the accessing stakeholder’s expertise with the intention to reduce silos across multiple documents. For the current research, the focus is on representations that are simple to implement, easy to maintain, and lend themselves to analysis.

The information in standards has been represented for specific applications such as Automated Code Checking (ACC) or SASE. Creating and maintaining these models parallel to the paper/digital document (i.e., digital twins) is challenging due to the limits of representations and the resources required for information extraction and validation (Nyman 1974, Zhang and El-Gohary 2016, Fuchs and Amor 2021). This also implies a significant maintenance cost for each revised version if the standard is not maintained in a format that facilitates simple translation into a representation, such as LegalDocML and LegalRuleML (Dimyadi et al. 2020), or if the format changes and invalidates the translation pipeline (assuming software translation). Modern NLP techniques have been explored for extraction and other tasks by researchers (e.g., Zhang and El-Gohary 2016 and Femmer et al. 2017) with varying levels of success, as reviewed by Fuchs and Amor (2022).

2.4.1.1 Decision Logic Tables

The first reported building standard representation other than text was developed by Fenves (1969) in the 1960s using decision tables or decision logic tables (DLT). DLT formulation uses first order logic (FOL), or predicate logic, to decompose standard provisions into “conditions” and “actions” which determine provision applicability and required actions, respectively. These statements are tabulated for each provision and can represent most provisions (those in FOL) precisely. DLT can be linked together using input and output variables, or datums, to map entire standards in order to check consistency, completeness, and unambiguity, but compiling the tables is an onerous process. FOL is limited by monotonic negation, meaning one cannot “unsatisfy” or "unapply" a condition after deeming a condition satisfied or applicable. FOL representations of a standard are common in ACC, where N3Logic (e.g., Dimyadi et al. 2015) and SWRL (Baumgärtel et al. 2015) are extensions developed to circumvent monotonic negation and other expressive limits of FOL. These approaches support if-then rule checking in a standard. Fenves' formulation was the basis of the 1980's reorganization of AISC Load Factor Resistance Design Code (1986) (Galambos 1992).

2.4.1.2 Information Network Representations

Fenves (1973) decomposed the American Institute of Steel Construction *Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings* (AISC 1969) generally into four levels of increasing resolution: the organization (outline), information network, DLT, and datums. A standard can be considered as a network of information, where nodes represent provisions, datums, or variables (depending on granularity) and their relationships are represented by edges. An example developed in the present research program for ACI 318-11 is shown in Figure 2.5. The mid-resolution information network model for AISC Specification (1969), developed by Fenves, was used to visually inspect the standard for logic loops (circular references) by identifying cycles in the network before a major restructuring.

Nyman et al. (1973) expand on the idea of information network representations of a standard into a 'functional-organizational' network, where functions are mapped as edges connecting datums. A complete functional network representing all input data transformations to output data for the entire AISC Specification (1969) was not completed (Nyman 1974). Rudimentary clustering algorithms were deployed but Nyman determined that the network model and algorithms of the time had many inconsistencies and limitations and predicted this portion of their research likely wouldn't be used to guide the AISC Specification restructuring.

ACI 318-77 was also modeled using a modified version of SASE by Noland and Feng (1975). Harris et al. (1979) used SASE in the analysis of the Applied Technology Council's (ATC) *Tentative Provisions for the Development of Seismic Regulations for Buildings* (ATC 1978), but this work languished with the standard never being published. This was the last known time an information network was built for the purpose of improving a standard. Throughout the 1980s, research shifted away from authorship aid to design aid with ACC. With that shift, limited logic/network representations evolved into more abstract, and later ontological, representations of standards that offered greater flexibility for wider applicability and potentially greater fidelity, which are better suited for ACC (Fenves et al. 1995). To date, no known research has been conducted relating the features of a building standard information network model to perceived complexity.

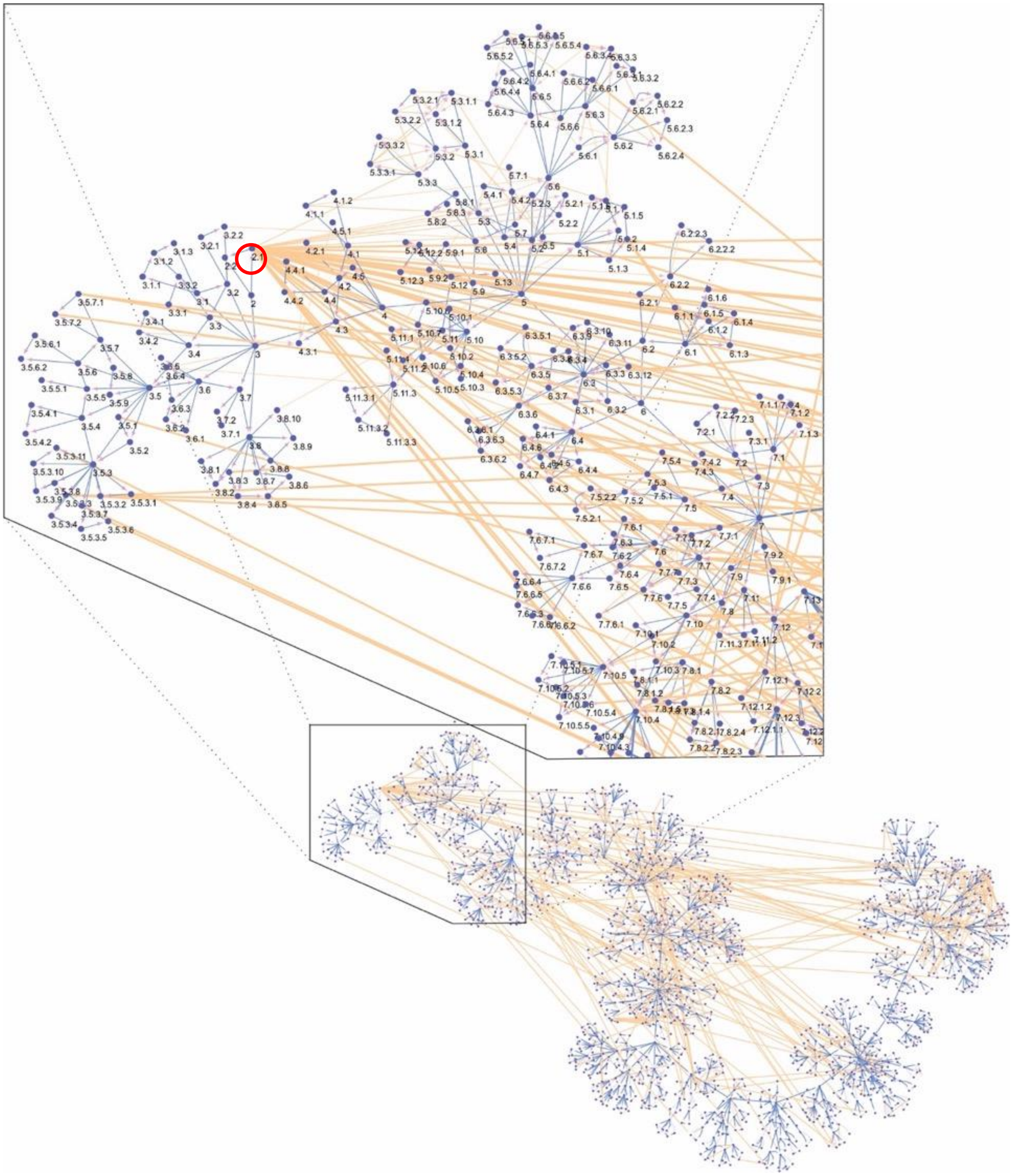


Figure 2.5 Reference information network of ACI 318-11. Organic layout based on implicit reference flow (blue). Explicit references (gold) show "short cuts" or diversions through the standard. Notice the global hub in the explicit network (top left). Features such as this could indicate a provision that is not in its optimal place in the standard (This particular node, ‘2.1 - Code Notation’, is probably not misplaced).

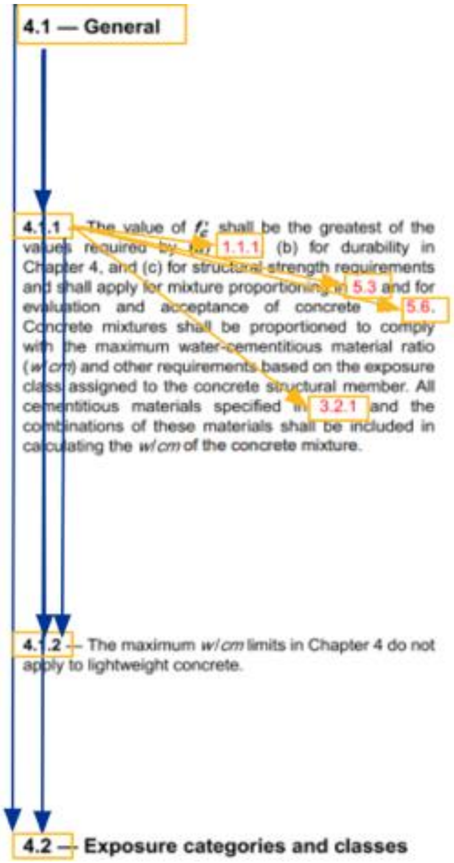
2.4.1.3 Other Representations

It is worth mentioning that there are several other building standard representations that have been proposed or implemented in practice but have been largely omitted from discussion here due to their impracticality for the objectives of this study. Nawari (2018) provides a succinct overview of standard models used in ACC and their evolution from Fenves' DLT to Ontological/Semantic Web Models. Semantic models are particularly useful for representing and characterizing domain specific representation knowledge systems (Pereira et al. 2016; Grilo et al. 2017). Semantic models of standards using Web Ontology Language (OWL) provide high-fidelity universal representations that allow for interoperability between various design software (Salama and El-Gohary 2016). IfcOWL is a robust ontological language that was developed to facilitate data exchange for building information modeling (BIM) across many industry stakeholders (Beetz et al. 2008). IfcOWL is believed to be capable of representing almost all building standard requirements. Additionally, semantic models can be represented by a graph and are much like the 'functional-organization' network described above. However, there are currently no complete semantic models of structural building standards publicly available for study and creation of such an IfcOWL model is resource and technologically intensive (Zhang and El-Gohary, 2016). Future advances in NLP or other automated methods may make these models simpler to build but substantial research challenges lie ahead and are worth pursuing on their own.

2.5 Network Structures and Metrics

Graph theory and network science are versatile and have been used to abstract, describe, and analyze systems across numerous domains and scales (Newman 2010). Network graphs can be used to model systems of discrete elements (nodes) and their relationships (edges). This versatility has led to applications too numerous to mention, but include transportation systems, biological systems, communication systems, artificial intelligence, economics, and systems engineering. Since 1979, the last known time an information network was created with the intention of improving a building design standard (ATC 1978, Harris et al. 1979), the body of network science knowledge has grown immensely, as have hardware capabilities and software availability. These factors indicate that it may be worthwhile to revisit the characterization of the structural network of standards, since characterization is now more efficient, and interpretations are [potentially] more meaningful.

From Section 2.4.1, there are two models at different resolutions that are considered practical and mature for this research; the reference network model and the functional network model. These models could be expanded by layering semantic models upon them, as they mature. In the reference network model, provisions in standards can be represented by nodes with their relationships represented by edges. A standard's reference network is directed, meaning an edge "points" from one node to the next, indicating a "flow". A reference network is considered a multiplex network since we assume it is at least composed of the implicit and explicit reference networks (Figure 2.5). For this research we attribute "explicit" to an edge, e_{ij}, initiating from the provision at node *i* which explicitly names the referenced provision at node *j* within the initiating provision (Figure 2.6). We attribute "implicit" to an edge representing the sequential flow (blue arrows in Figure 2.6) from the root of the first chapter to all other chapters and sequentially through them until reaching leaf nodes, which point to no other provisions (Provision 4.1.2 in Figure 2.6). The directed graph representation of standard with only explicit or implicit edges are referred to as the explicit and implicit networks, respectively, or as the complete network when combined. 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 discussion of various properties and metrics, sorted by scale from most refined to most general (neighbor, community and global) are presented in the following sections. A substantial review of network metrics is presented by Newman (2010).



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 2.6 Implicit (blue) and explicit (yellow) references within the standard compose their namesake networks in the directed graph representations. Combined, in this work these networks are refered to as the complete network of the standard.

2.5.1 Neighbor Scale

Degree[ǂ] and centrality[ǂ] metrics can be used to identify important nodes locally and globally by assuming that important nodes have higher degree (number of connections) or belong to more paths[ǂ]. The important nodes are known colloquially as brokers, bridges, or bottlenecks in the system. Various centrality metrics and their uses are presented by Koshcutzki et al. (2005). Betweenness centrality, defined as the number of geodesic paths[ǂ] that pass through a node or edge, is a useful metric for identifying clusters (discussed below).

Regular patterns or subgraphs that are repeated in the network more often than random are known as motifs. Motifs can be indicators of robustness and modularity in networks. Conserved or conserving motifs in a standard may be perceived as continuity and consistency to the user.

2.5.2 Community Scale

Communities can be thought of as networks within networks. Connections within the community are dense, but between communities the connections are sparser. Nodes with similar functions tend to cluster together, which means that a strong community detection algorithm can infer similar functions. For a standard reference network, the implicit references are likely to form clusters within each chapter. However, the explicit references between these clusters will be most interesting to study, as they could indicate provisions that are "misplaced" into other chapters or emergent functions across chapters. Similarly, a large chapter may contain multiple clusters, which could indicate the chapter could be split to mitigate potential confusion. Newman (2004) describes several approaches and formalizes the concept of modularity in networks, which allows for an objective measure of success of community identification. Girvan and Newman (2002) also present an algorithm for detecting any number of communities (k-communities) by removing edges with high betweenness, which is computationally intensive but robust. The Girvan-Newman algorithm is of note because other common community-finding algorithms bisect the network successively, which is not useful for the present research.

2.5.3 Global Scale

Small world networks[†] have shortcuts through an otherwise well-organized network that allow for traversing the network more quickly than through the well-organized portions. This concept is often described through the game “six degrees of separation” (or [Kevin] Bacon’s Law), first explored by Stanley Milgram. Milgram mailed packages to strangers in Omaha, Nebraska and instructed them to forward the packages through their social networks to a stockbroker in Boston (Travers and Milgram 1969). Milgram found that his packages reached their intended recipient with a surprisingly small number of intermediaries (~5), indicating an efficient social network structure for information transfer. Watts and Strogatz (1998) formally characterized the small world property through the characteristic path length and global clustering coefficient while showing small worlds existed in a variety of examples including power grids and systems of neurons.

The characteristic path length is the mean geodesic path length found by summing the geodesic paths from every node to every other node and dividing by the number of geodesic paths. The clustering coefficient, sometimes called transitivity, is the ratio of connected triangles to triples of nodes in the network. Costa et al. (2007) provides further details on network properties related to clustering. Small worlds often have an over-abundance of hubs, which are high degree nodes potentially useful in efficiently disseminating knowledge. Kleinberg (2000) noted that not only are small networks structured efficiently, but the people or nodes are “intelligent” and know where shortcuts are most likely to occur. Designing a building design standard network to take advantage of small worldliness could lead to easier navigation and a better user experience. Ensuring that the user knows how to use the “shortcuts” efficiently, through guides or other material, is likely to be important in a small world reference network.

Random networks[†] that grow by adding more nodes that preference already well-connected nodes are known as scale-free[†] networks, since their node connectivity follows a scale-free power-law distribution (Barabási et al. 1999). Large networks that exhibit this property, such as the nervous system or the World Wide Web, self-organize into a scale-free state. Modest-sized networks, the size of a large building design standard, may not have enough features to be scale-free, and smaller standards are unlikely to demonstrate this property.

At small scales, the network structure (or lack of structure) may not present challenges to its function. However, as the system continues to grow, the connections and clusters that form the underlying structure become increasingly relevant to how the system functions (de Weck et al. 2011). Scale-free networks can be considered resilient because if a node fails to function, there is only a small probability that the node is a hub, so the overall functionality is not likely to be affected. The corollary is that if the node that fails is a hub in a scale-free network, it could be catastrophic to the network's function. This points to a relationship between high connectivity and lethality in the system. As an example, in the context of a building design standard, a failing node could be a provision with many dependencies that is particularly troublesome for users to parse or implement. If many other provisions depend on this hub, the likelihood of any of them being correctly satisfied is reduced.

2.5.4 Entropy

Information-based entropy measures attempt to quantify the uncertainty in transmitting information from a transmitter to a receiver. The concept of information entropy was developed in the field of signal processing and is commonly used in data compression, which could be useful in extending the convincing "standards as signal communication" metaphor made by Bulleit (2012).

Bulleit's metaphor arranges the encoding SWB as the transmitter, the building standard as the channel, and the decoding engineer as the receiver. In signal processing, Shannon entropy estimates the upper limit of information that can be sent through a communication channel (or network) and the corresponding lower bound noise levels expected in the output (decoded) signal.

An analogy can be drawn to the cognitive limit, which is the maximum information a person can track during a task, discussed in Gallotti (2016). Entropy-based measures are defined by the network invariants on which they depend, such as number of nodes, neighbors, distances, degree distributions, or network matrices such as the Randic or Laplacian (Tranquillo 2019). Entropy methods are sometimes used as complexity measures of networks on their own, although this is recognized as being flawed because the metric is based on physical properties and therefore comparisons between networks are not relative (Morzy et al. 2017). Entropy fooling graphs exist and are not trivial, because entropy essentially equates complexity with network randomness. These detractors being acknowledged, entropy measures could still prove useful as an indicator of complexity in standards networks.

2.6 Natural Language Processing

Natural Language Processing (NLP) is a set of techniques developed in computational linguistics to process and understand human language. NLP tasks can be "low-level", such as tokenization, part of speech tagging and pattern matching. Alternatively, NLP tasks can be "high-level", such as information extraction, question answering, classification, or translation which are fed by lower-level tasks. As reviewed by Fuchs (2021), NLP has not been extensively explored in AEC applications, but has received more attention lately in the field of automated code compliance checking (ACCC) due to the growing prevalence of integrated BIM. A review of NLP in building code interpretation is presented in Fuchs and Amor (2022). Here, NLP is explored (1) as a way to extract text from a standard and (2) to generate semantic context between provisions. Neither of these tasks expand the field of NLP, but the second appears to be a novel application of semantic similarity between provisions and shows potential for exploring relations within and between building standards.

2.6.1 Text Extraction

Text extraction and digitization of documents such as menus or instruction manuals can now be accomplished reliably and almost instantaneously with most smartphones. The challenges with extracting text from standards arise from (1) their large size, (2) the extraneous information on many pages, (3) identifying and representing tables and (4) identifying and representing graphical presentations, (5) identifying and representing symbol and equation representations, (6) corrupted or incorrect file metadata, (7) maintaining relationships during extraction (i.e., provision title and content), and (8) validation. Open-source NLP packages for Python exist for extracting and manipulating information from PDF and other file types. Minimizing information extraction by maintaining metadata during authoring is a worthwhile task to undergo as standards transition from paper to digital representations.

Once the desired text is extracted, a set of regular expressions (regex) can be used to match patterns in the text (i.e., provision titles) in order to “clean” the text or to label and extract certain portions. Regex must be crafted to only match what the user seeks; otherwise ‘Type I’ (false positive match) and ‘Type II’ (false negative) errors occur. Type I errors occur when the regex is too restrictive, while Type II errors occur when the pattern is not strict enough. Both error types can occur if the text is irregularly formatted, such as inconsistent whitespace or newline characters when those characters are included in the pattern. This is the case for provision titles, for instance, since the text extraction process almost always and nearly exclusively resulted in a provision title formatted “XX.XX +” beginning after newline.

2.6.2 Text Embeddings

An embedding[†] is a dense vector representation of the meaning of a word or group of words (Mikolov et al. 2013). During training, embedding algorithms orient tokens (words, word parts, characters, etc.) in a vector space so that predictions about surrounding tokens can be made more accurately. This results in tokens that share a common context in the training corpus being located nearer to each other in the model space than those that do not. Embeddings can be static or contextual (dynamic). A pre-trained language model with static embeddings (e.g., word2vec or GLoVe) will *look up* an input token in the model space then output a predefined embedding. That means that each embedding represents all of a token’s polysemes found in the corpus. However, a contextual model (e.g., GPT3 or BERT) will *construct* an embedding (for each token and for the sentence as a whole) based on all the tokens in the sentence and their positions.

A word must first be tokenized to query a pre-trained language model for an embedding. Tokenization requirements vary based on the language model, but the simplest tokenization breaks conjunctions into parts, if necessary (e.g., ‘Isn’t’ → [‘Is’, ‘n’t’]), and notes when sentences begin and end. Stop words, that often contribute little to the meaning of a sentence, can be removed at this stage of processing. Sometimes tokens will be lemmatized, and other cleaning operations will be performed to improve consistency (e.g. [‘Is’, ‘n’t’] → [‘is’, ‘not’]). To represent a group of words, static embeddings for multiple tokens can be pooled via averaging (mean pooling), taking the maximum (max pooling), or some other function.

To develop the model space, a neural network is trained to predict words in a training corpus; commonly using variations on one of two algorithms: continuous bag of words (CBOW) or skip-grams (skip-gram) (Mikolov et al. 2013). The CBOW algorithm trains the network by targeting the prediction of a single word based on a context window of words surrounding it (typically 5-10 words), with no consideration for word sequence, hence a ‘bag of words. The skip-gram algorithm predicts words in a window surrounding a given word based on the current word and weighs nearer words more heavily than distant words. Once the model is trained and the embedding space is generated (which are synonymous for basic implementations), language tasks such as text search, text classification, question-answering, translations, and summarizations can be performed.

Many pre-trained models are available online, such as “en_core_web_lg”, freely available from spaCy (an open-source NLP library/platform for industrial use), which has 514,000 unique embeddings or vectors which each represent an English word in 300 dimensions trained on written web sources (Honnibal et al. 2020). The spaCy model is also used for tagging, parsing, lemmatizing, and named entity recognition. Pre-trained language models can be ‘fine-tuned’ via transfer learning to facilitate downstream NLP tasks. Fine-tuning typically consists of supervised training of the general-purpose pre-trained model with labels representing application or domain-specific parameters. For example, the model can be trained on sentence pairs that are similar and dissimilar to each other, as rated by humans or based on their proximity to one another in a corpus. Models can also be fine-tuned to better understand a knowledge-domain’s polysemes (e.g. a ‘moment’ in time versus a bending ‘moment’), however a civil engineering corpus was not available for this research.

Drawbacks of using a pre-trained model that has not been fine-tuned on a domain is that domain-specific words (or symbols) that do not appear in the training corpus and will be assigned a zero-vector and those with polysemes will be represented as only one token in the model space. Further, “en_core_web_lg” and other language models of this class typically use vector averaging to represent semantic meaning of more than one word. Vector averaging is simply the sum of all tokens’ vectors in the call divided by the number of tokens called. Vector averaging is not sensitive to the order of the words, such that two documents expressing the same meaning with dissimilar wording will return different vectors, while two documents that contain the same words (regardless of order) yet holding different meanings will return identical vectors. For these reasons, the utility of these models for semantic analysis of multiple words or outside the training domain is limited.

As an example, Table 2.2 shows the outcome of vector averaging applied to Clause 5.9 of ISO 22156:2021 (see Chapter 5). The intent of the clause should be clear. The title is “*5.9 Maintenance, inspectability and replacement considerations*”; the first sentence provides a “justification” and the second and third sentences provide the requirements. Depending on the sampling boundary the resulting average embeddings are very different. Sampling the entire clause (Sample 1), the average word embedding quickly drifts away from more descriptive locations (‘bamboo’, ‘culm’), indicated by large magnitudes, in the embedding space towards embeddings representing broader topics or ideas (‘reasons’, ‘possible’), indicated by lower magnitudes, which occur more frequently in the training corpus. By reducing the number of words in the sample, the washout effect of vector averaging is also reduced (Sample 2).

Table 2.2 Example of vector averaging of ISO 22156:2021 Clause 5.9

	Sample 1	**Sample 2**
Initial Sample	**5.9 Maintenance, inspectability and replacement considerations** For a variety of reasons, bamboo culms may split longitudinally or be otherwise damaged when in service. To the extent possible, provision should be made to permit maintenance and inspection of bamboo load- bearing members; particularly members forming part of a non-redundant load path. To the extent possible, consideration of the future need to replace individual culms in a member or structure should be made.	**5.9 Maintenance, inspectability and replacement considerations** For a variety of reasons, bamboo culms may split longitudinally or be otherwise damaged when in service.
Removing stop words:	‘5.9’, ‘Maintenance’, ‘inspectability’, ‘replacement’, ‘considerations’, ‘variety’, ‘reasons’, ‘bamboo’, ‘culms’, ‘split’, ‘longitudinally’, ‘damaged’, ‘service’, ‘extent’, ‘possible’, ‘provision’, ‘permit’, ‘maintenance’, ‘inspection’, ‘bamboo’, ‘load-‘, ‘bearing’, ‘members’, ‘particularly’, ‘members’, ‘forming’, ‘non’, ‘-‘, ‘redundant’, ‘load’, ‘path’, ‘extent’, ‘possible’, ‘consideration’, ‘future’, ‘need’, ‘replace’, ‘individual’, ‘culms’, ‘member’, ‘structure’]	‘5.9’, ‘Maintenance’, ‘inspectability’, ‘replacement’, ‘considerations’, ‘variety’, ‘reasons’, ‘bamboo’, ‘culms’, ‘split’, ‘longitudinally’, ‘damaged’, ‘service’
Vector magnitudes (identifies tokens not found in corpus)	[‘6.26’, ‘6.67’, **‘0.00’**, ‘6.64’, ‘5.87’, ‘5.68’, ‘4.93’, ‘7.10’, ‘8.43’, ‘5.55’, ‘8.40’, ‘6.82’, ‘6.63’, ‘5.22’, ‘5.06’, ‘6.64’, ‘6.06’, ‘6.67’, ‘6.99’, ‘7.10’, **‘0.00’**, ‘6.06’, ‘6.73’, ‘5.19’, ‘6.73’, ‘6.50’, ‘6.36’, ‘5.60’, ‘6.09’, ‘6.38’, ‘6.44’, ‘5.22’, ‘5.06’, ‘5.24’, ‘5.45’, ‘5.17’, ‘5.67’, ‘5.84’, ‘8.43’, ‘6.66’, ‘6.35’]	[‘6.26’, ‘6.67’, **‘0.00’**, ‘6.64’, ‘5.87’, ‘5.68’, ‘4.93’, ‘7.10’, ‘8.43’, ‘5.55’, ‘8.40’, ‘6.82’, ‘6.63’]
Closest 10 tokens in embedding space:	‘NECESSARY’, ‘Necessary’, ‘necessary’, ‘possible’, ‘Possible’, ‘POSSIBLE’, ‘therefore’, ‘Therefore’, ‘THEREFORE’, ‘certain’	‘MAINTENANCE’, ‘Maintenance’, ‘maintenance’, ‘components’, ‘COMPONENTS’, ‘Components’, ‘necessary’, ‘Necessary’, ‘NECESSARY’, ‘Existing’

Many more advanced machine learning models for NLP tasks have been developed for both academic and industry use[7]. Of note are those with context-sensitive transformer architecture such as Google's BERT (Devlin et al. 2018) and OpenAI's GPT3 (Brown et al. 2020), which have been trained on billions of tokens scraped from the internet. These models are distinguished by their 'attention' mechanism by which the algorithm relatively weighs the semantic importance of tokens in a sentence or paragraph (the token's embedding), enabling an uncanny mimicking of human language processing including rich text generation, question answering, and translation. Additionally, the models use WordPiece tokenization which nearly eliminates zero-vectors (Song and Zhou 2021). If an unknown word is encountered during tokenization, it is broken into common sub-words or even individual characters before embedment, if necessary. This means that all text can be represented and processed by the algorithm on some level, although words that were never encountered during training will still have a magnitude close to zero. Access to these larger pre-trained models is available through API services. In this research, OpenAI's GTP-3 Curie[8] and spaCy[9] language models are used to explore the semantic relations between provisions.

2.6.3 Semantic Similarity

Semantic similarity in NLP, as discussed here and reviewed by Chandrasekaran and Mago (2021), is a measure of relatedness between two text objects, based either on their information content or their relatedness (connections) to other objects. The cosine similarity (angle of the cosine given by Eq. 2.1) and the Euclidean distance (Eq. 2.2), between two vector embeddings are

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[7] hugginface.co currently lists over 100,000 public models

[8] "text-similarity-curie-001", now replaced by "text-embedding-curie-001"

[9] en_core_web_lg v.3.2.0 , https://spacy.io/models/en#en_core_web_lg

the most commonly adopted similarity metrics. Both are measures of distance between discrete data oriented in an n-dimensional space. In fact, the L2-normalized Euclidean distance and the cosine angle will result in the same ordering for any comparison of vectors. The normalized cosine *angle,* independent of the size of the vector space, ranges from -1 to +1, which corresponds to opposite and identical vectors, respectively. Cosine *similarity* is typically restricted to positive space (0 to +1), as the embeddings capture the *presence* of tokens in the corpus. The cosine angle is slightly faster to compute and is insensitive to vector magnitudes of non-normalized embedding spaces, leading to more prevalent use in NLP.

$$Sim_C(x,y) = \cos(\theta) = \frac{x \cdot y}{\|x\| \cdot \|y\|} = \frac{\sum_{i=1}^{n}(x_i \cdot y_i)}{\sqrt{\sum_{i=1}^{n} x_i^2} \cdot \sqrt{\sum_{i=1}^{n} y_i^2}} \qquad (2.1)$$

$$Sim_E(x,y) = \|x - y\|_2 = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2} \qquad (2.2)$$

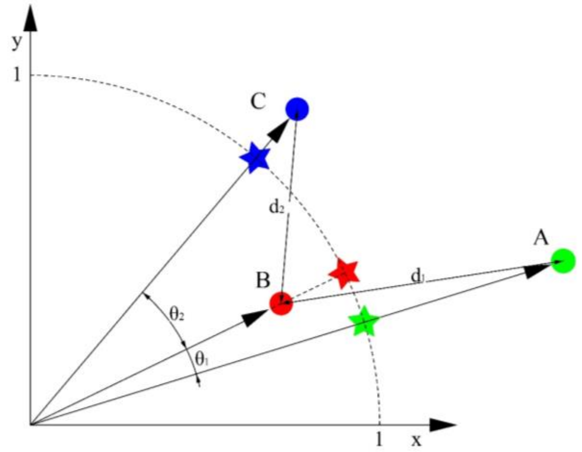


Figure 2.7 Euclidean and cosine similarities. The Euclidean distance (d) and angle (θ) between vectors **B** and **A,** and **B** and **C** are shown. By inspection, $d_1 > d_2$ and $\theta_1 < \theta_2$, giving conflicting similarity scores between the vectors. The same comparison with L2-normalized vectors (stars) yields $d_1 < d_2$ and $\theta_1 < \theta_2$. Where vector magnitudes are semantically unimportant or misleading (e.g. the number of times a word occurs in the corpus), cosine similarity is preferred over Euclidean distances. Both yield the same results for comparisons between datum in L2-normalized space.

2.7 Chapter Summary

Building design standards are valuable socio-technical systems intended to reduce uncertainty among stakeholders of the AEC industry by regulating their behavior. Standards serve to enhance occupant safety, efficiency, economy, and other desirable qualities by communicating domain knowledge from the writers to the end-users. Standard development is typically undertaken without a *complete* understanding of the subject or even the limits of that understanding. Additionally, design standards must ‘anticipate’ their being applied to innovative systems and, at times, being applied in manners not intended by the SWB. This can present challenges to end-users as a standard and its industry matures. A standard may be ambiguous, illogical, conflicting, overly restrictive, or otherwise confusing to the end-user, undermining the standard and the intent of the SWB. The review presented here indicates, unsurprisingly, that end-users perceive complexity in standards when the standard performs poorly, or outside of their expectations. Simply, complexity exists when competent end-users are uncertain whether their design does or does not satisfy requirements or are uncertain whether satisfied requirements produce quality designs. Tools exist to manage complexity (reduce uncertainty), such as alternative communication channels (e.g., guides and commentary) and references between relevant provisions. However, these tools can actively work against the success of the standard. End-users are challenged to manage complicated referencing and tend to point immediately to an increase in the number of provisions or pages in a document as evidence of complexity.

Strictly measuring complexity of a standard in the physical dimension is inherently flawed, but by adopting a performance-based definition more useful metrics can be identified. Measuring the performance of a standard is much more challenging than measuring its physical properties. Previous research, particularly that of Angelino et al. (2014), has identified important qualities of standards from the perspective of stakeholders, some of which might be resolved into functional requirements. Syntax and grammar can be made consistent using style guides to enhance semantic clarity for the reader, but rules for organizing information more broadly across the standard may be more challenging to implement.

The review presented herein shows that end-users desire a consistent and logical structure that facilitates locating the necessary provisions related to a design instance. A trend in design standard development is to have the natural hierarchy within the standard mirror a design workflow, in an attempt to mimic the end-users' most-probable mental map of the design space. Arguably, other users may favor a standard that follows a mental map of the typical conformance checks one performs of a design instance, rather than the 'typical' design workflow. The difference between these instances may relate to the experience of the designer; the mental map of the design or conformance space likely evolves with experience. Additionally, maintaining consistency in the lower-level structures of the hierarchy are likely useful for orienting end-users who may be unfamiliar with portions of the standard, as deeper hierarchies will represent ad-hoc (less common) tasks. Given user feedback on a standard, one may be able to quantify or qualify how favorable its structural characteristics are. Identifying desirable structures in design standards could not only help better organize standards, but also better understand end-users' mental maps which could be particularly useful as the next generation of standards transition to digital formats.

Network models are underexplored abstractions of standards that could be useful for understanding how the structure of a standard and the user experience are linked. A variety of networks in the fields of physical, biological, and social sciences have been studied to better understand the behavior of the systems they represent. Previous network representations of standards, largely conducted before 1980, noted limitations imposed by network topology understanding, computation-intensive algorithms, hardware capabilities, and the manpower-intensive abstraction process. With modern computing many of these limitations can be overcome, making the time may right to revisit network representations of standards.

NLP is a rapidly growing field that is useful in this work for automating the text extraction and abstraction process. Features of the standard such as provision titles, references, and other datum (e.g., variables or noun and verb phrases) can be extracted from the text for analysis or to build a robust network representation. The interactions and relationships between features can also be captured using NLP for use in the network representations. Of interest here are the semantic relationships between datum, represented as embeddings, since these reflect the end-users' understanding of the datum, albeit currently to unknown and limited levels of precision and accuracy. Embeddings are useful for measuring relatedness which can be leveraged to automate question-answering, categorization, summarization, and link-prediction (recommendation) tasks, for example. Many research gaps exist in the semantic understanding of construction documents. The relationship between the structure of a design standard and the semantic information captured within each provision's embedding is underexplored, with no known instances in the literature.

3.0 Perception Survey of ACI 318-11 to ACI 318-14 Reorganization

Much of the content of this chapter was published as ‘7 Years on: Perception Survey of ACI 318-11 to ACI 318-14 Reorganization’ in *Concrete International* (Rogers and Harries, 2022).

Building design standards provide numerous benefits to both society and industry and, in the past century, have become central to design and construction workflows. Although every ounce of efficiency is squeezed out of the materials used and labor practices we adopt, relatively little consideration is given to improving the efficient use of standards, raising the question: *Is the value of design standards being undermined by a steady increase in their complexity?*

Anecdotally, as described at length in Section 2.2.1, users often point to a standard’s increasing size, number of provisions, or reliance on supporting documentation to locate and satisfy requirements as evidence that a standard is more complex than its previous editions. Yet standards must evolve to reflect an ever-growing body of knowledge and to accommodate novel requirements brought about by developing issues, such as innovative technologies, shifts in societal values, and changing climate. If their continued expansion is not carefully conducted, bloated standards will make it challenging for users to be confident that their designs are compliant.

As standards evolve and grow, requirements can become obfuscated by ambiguous, inconsistent, or illogical phrasing. Additionally, connections between requirements can be difficult to understand, particularly when the connected provisions are physically distant from one another in a standard, become “too numerous” to efficiently manage in a workflow, or when multiple standards must be referenced simultaneously. The user is likely to register the greater resource intensity required to parse the standard – be it time, mental energy, or sheer frustration – as complexity in the document. An intuitive structure, the way the document is explicitly and implicitly connected, can enable users to easily identify, locate, and interpret standard provisions for the job at hand, ensuring efficient use of resources, higher confidence in achieving conformance, and greater user satisfaction with the standard (Frosch 2009).

Consistently identifying "complex" or "intuitive" document structures is not a straightforward process. Standards are socio-technical systems; the system exists to serve stakeholders' needs. Therefore, stakeholder perception must be understood if we are to understand the quality of a standard (de Weck 2011). The purpose or function of a standard is often unique to each stakeholder group but to be considered of any use or quality, the standard must serve, not frustrate, the majority of stakeholders in most instances. By this notion, understanding the user experience becomes critical to the success of the standard. User satisfaction must be influenced by the structure of a standards document (as well as innumerable other features). Yet, very little research has been conducted on the implementation of a structure that allows for growth and expansion while minimizing perceived complexity.

The restructuring of ACI's flagship document, "Building Code Requirements for Structural Concrete and Commentary (ACI 318)," from the 2011 to 2014 editions provides a unique opportunity to compare the structure of two standards that otherwise contain essentially identical information and objectives. Although some provisions were split to accommodate the new format, and some equations were converted to tables or figures, the vast majority were left unaltered to minimize confusion anticipated by the vast reorganization (Frosch 2009). This allows for study of the effect that restructuring ACI 318 had on users' experience and provides a small control for the influence that new or altered requirements may have on user-perceived complexity. It has been reported anecdotally that many ACI 318 users believe the reorganization has made ACI 318 easier to use. However, these perceptions have not been systematically gathered and evaluated.

Additionally, little research has been conducted on the mechanisms by which the restructuring may have reduced perceived complexity. Such study could lead to valuable lessons learned for ACI and other standard-writing bodies.

3.1 Background

ACI 318 is the prescribed design standard for structural concrete in the United States and is adopted (and adapted) by multiple building authorities abroad; it is also published by ACI in a Spanish-language version.

The first version of what would become ACI 318 was 14 pages and appeared in 1910 (Poston 2019). In 1941, the first document referred to as 'ACI 318' appeared. A significant revision, the first inclusion of the ultimate strength method of design (used today) in an appendix to the working stress design based main document, was published in 1956. By 1971, the ultimate strength method of design comprised the main body of the standard. The side-by-side code and commentary format still in use today was introduced in the 1989 edition. The last significant technical revision was 1971, when the ultimate stress design methodology was fully specified and an appendix for seismic design was added. From 1971 to the mid-2000's, knowledge of constituent materials and the behavior of structural concrete has steadily grown. This has been encoded into ACI 318 in a mostly ad-hoc manner, with little global planning.

ACI 318 grew from 750 provisions and 250 cross references in 1971 to over 2500 provisions and 1500 cross references in 2008; both measures are potential indicators of complexity. The organization of the document, found by many to be nonintuitive, required engineers to practically memorize locations of key design requirements, which presented a steep learning curve and a demanding investment of inexperienced engineers' time. Ultimately, the 2011 version of ACI 318 was described as a "complex document that had become confusing and often off-putting for its structural engineering users" (Kopczynski, 2014). A survey of design professionals found "angst…a feeling of uncertainty about when a design is concluded and that all necessary provisions of the code have been satisfied" (Poston, 2009). Among other things, respondents suggested a reorganization of the standard that better follows the design process. In 2006, a steering committee recommended to improve the user experience by reorganizing ACI 318. The primary objective was to ensure that designers could be confident their designs were compliant with the standard.

At least three global restructuring principles were explored: layering to assist computerization, sectional behavior-based design, and member-based design. After considerable debate, the task group settled on a member-based design approach, then identified several development principles to guide the restructuring before developing draft outlines and chapters for approval. The guidelines adopted are reported by Dolan and Feldman (2009) as follows:

1. *Eliminate duplication* [of provisions] *to the extent possible.*
2. *Use figures and tables* [in lieu of text descriptions] *providing they lead to unique and reproducible results.*
3. *Establish a hierarchy with the simplest method of design first and more complex approaches as alternatives. This provides the user with a choice of design efforts.*
4. *Establish a format in which the user could go to a member chapter and be assured that all provisions for that member are identified and satisfied.*
5. *Focus on performance requirements where possible with prescriptive options following as a deemed-to-satisfy the approach.*
6. *Initially keep every existing provision and deliberately remove duplication and identify gaps resulting from the new format.*
7. *Improve the visibility of provisions addressing structural integrity.*
8. *Retain the side-by-side Code-Commentary format.*

An implication of the third guideline is that simplified approaches to design are necessarily more conservative, resulting, potentially, in less efficient use of material. This highlights the conflict between ease of use of the design document and performance objectives of the artifact being designed. In this sense, the third and fifth guideline could be seen as being in conflict.

The organization of ACI 318-11 (shown in Table 3.1) was a mixture of behavior, member, and process-based chapters that essentially followed the framework established in the 1971 edition. In the reorganized ACI 318-14 (Table 3.1), prerequisite knowledge required to design, such as loading and structural analysis methods, is presented first in Chapters 1 through 6. Following these are member chapters 7 through 14 organized to follow the flow of forces (and typical design) through a structure. Connection and detailing chapters 15 through 17 then follow. An innovation in ACI 318-14 was the development of so-called “toolbox” chapters (Chapters 19 through 25), which collect common concepts used across the member design chapters. This reduced duplication but increased the number of references from the member design chapters. The effect is evident by tracking the ‘two-way slabs’ Chapter 13 from ACI 318-11 shown in Figure 3.1 and comparing this to the similar ACI 318-14 ‘two-way slabs’ Chapter 8 in Figure 3.2. Total explicit references and explicit references out of ‘two-way slabs’ almost double with the 2014 revision, while incoming references remain constant. Furthermore, each member-based chapter was structured in an eight-point outline which mirrored the typical design strategy (Frosch 2009):

M.1 Scope
M.2 General
M.3 Design Limits
M.4 Required Strength
M.5 Nominal Strength
M.6 Minimum Reinforcement
M.7 Detailing
M.8 Construction

A comparison of the outlines of ACI 318-11 and ACI 318-14 is shown in Table 3.1.

Table 3.1 Chapter level reorganization of ACI 318-11 to ACI 318-14
adapted from Ghosh (2016).

ACI 318-11		ACI 318-14		Comment
Description	**Chapter – Title**	**Description**	**Chapter – Title**	
Introductory	1 – General Requirements	Introductory	1 – General	
	2 – Notation and Definitions		2 – Notation and Terminology	
	3 – Materials		3 – Referenced Standards	
Materials/ Construction	4 – Durability Requirements	Other	4 – Structural System Requirements	New
	5 – Concrete Quality, Mixing, and Placing		5 – Loads	
	6 – Formwork, Embedded Pipes, and Construction Joints		6 – Structural Analysis	
	7 – Details of Reinforcement	Member-based	7 -One-way Slabs	
Other	8 – Analysis and Design – General Considerations		8 – Two- way Slabs	
	9 – Strength and Serviceability Requirements		9 – Beams	
Behavior-based	10 – Flexure and Axial Loads		10 – Columns	
	11 – Shear and Torsion		11- Walls	
	12 – Development and Splices of Reinforcement		12 – Diaphragms	New
Member-based	13 – Two-way Slabs Systems		13 – Foundation	
	14 – Walls	Other	14 – Plain Concrete	Intact
	15 – Footings	Connections	15 – Beam-Column and Slab-column joints	
Other	16 – Precast Concrete		16 – Connections between Members	
	17 – Composite Concrete Flexural Members		17 – Anchoring to Concrete	Intact
	18 – Prestressed concrete	Other	18 – Earthquake-Resistant Structures	Intact
	19 – Shells and Folded Plate Members	Materials	19 – Code Requirements for Thin Shells and Commentary	ACI 318.2
	20 – Strength Evaluation of Existing Structures		20 – Steel Reinforcement Properties, Durability and Embedments	
	21- Earth-quake Resistant Structures	Toolbox	21 – Strength Reduction Factors	
	22 – Structural Plain Concrete		22 – Sectional Strength	
	A – Strut-and-Tie Models		23 – Strut-and-Tie models	Intact
	B. Alternative Provisions for Reinforced and Prestressed Concrete Flexural and Compression Members		24 – Serviceability Requirements	
	C. Alternative Load and Strength Reduction Factors		25 – Reinforcement Details	
	D. Anchoring to Concrete	Construction	26 – Construction Documents and Inspection	
		Other	27 – Strength Evaluation of Existing Structures	Intact

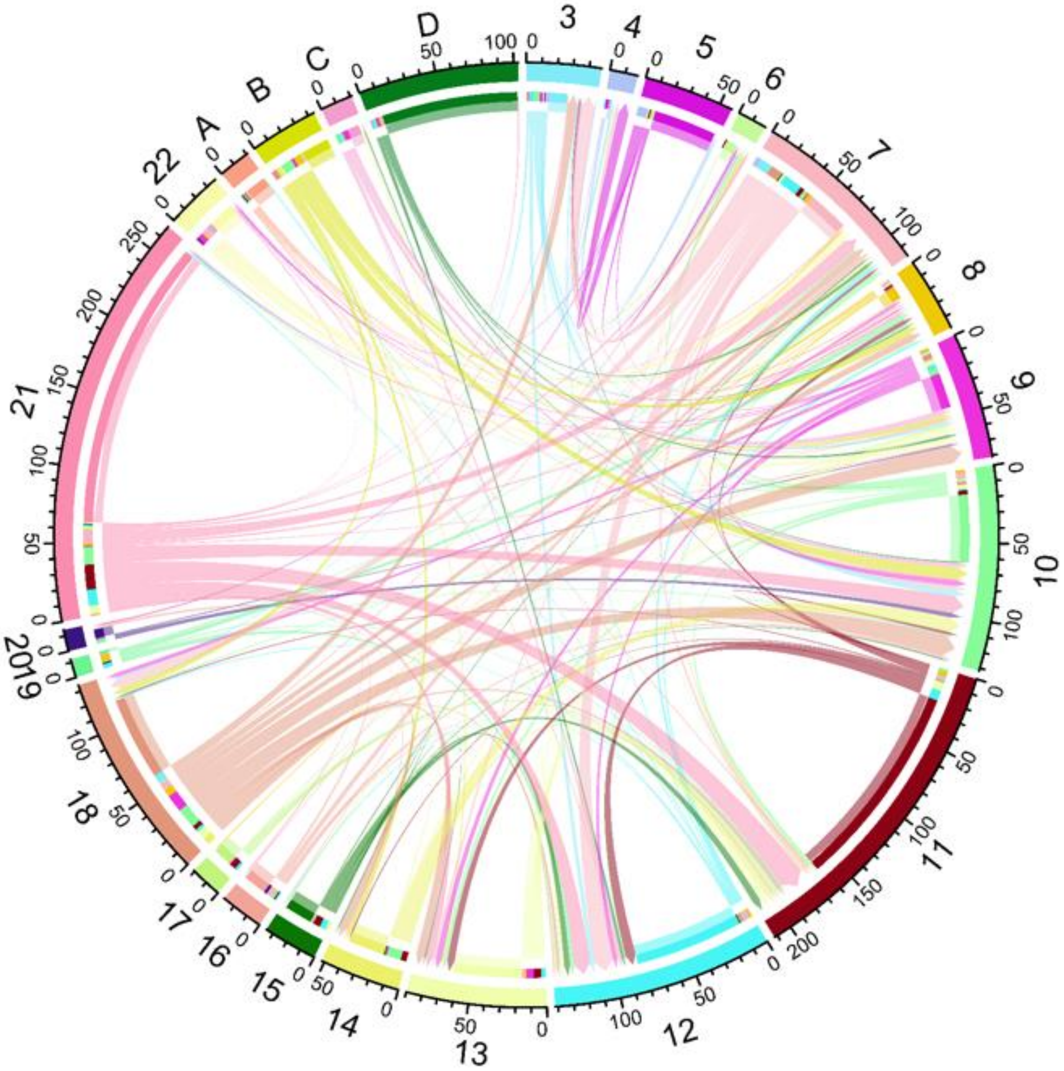


Figure 3.1 ACI 318-11 chord diagram. This diagram shows all the explicit internal references between chapters within ACI 318-11. Arrows point from the originating provision to the referenced provision (colors have no meaning and are simply provided for clarity). Counts with no arrows (blank peripheral blocks) represent self-references within the chapter.

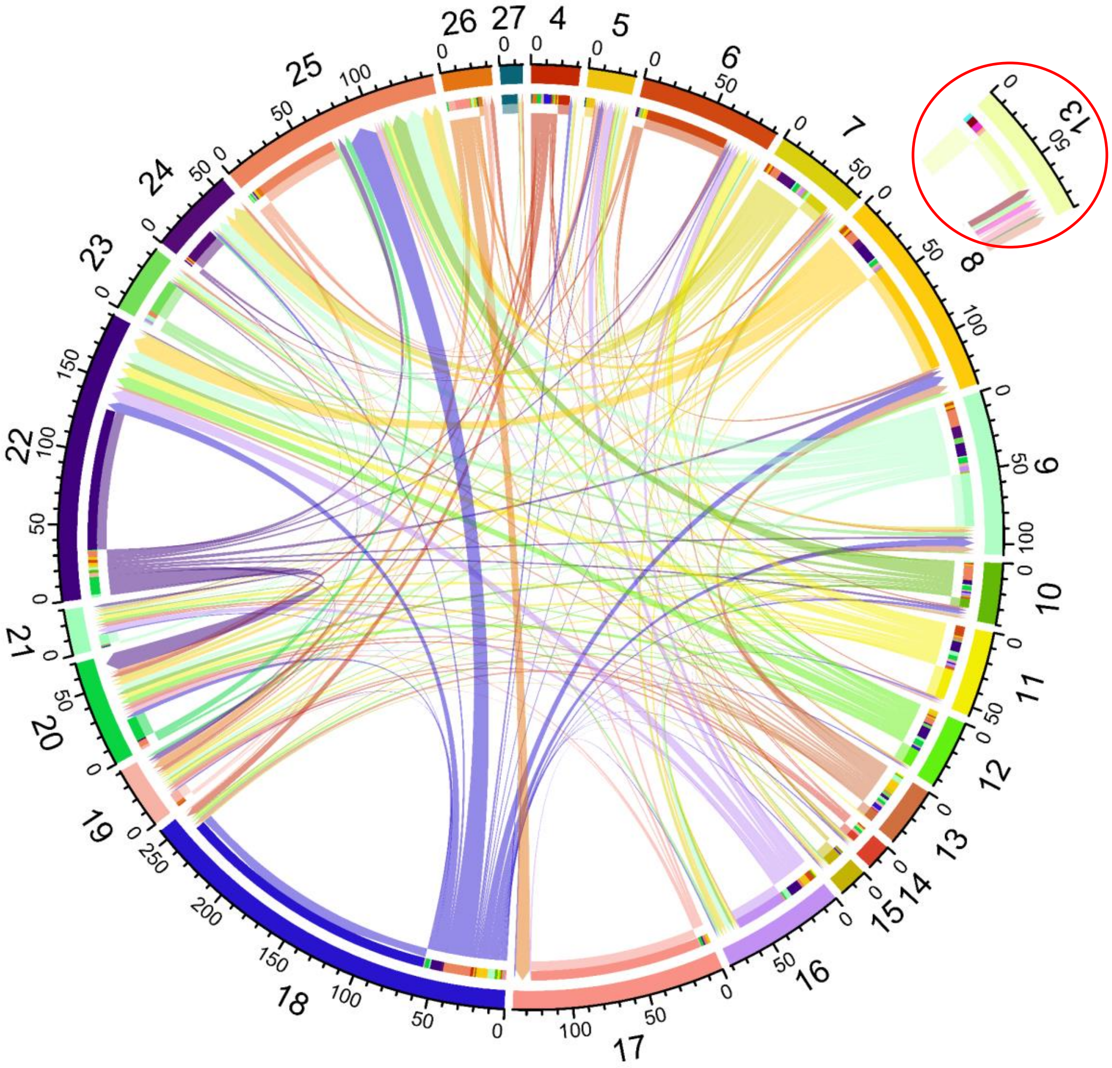


Figure 3.2 ACI 318-14 chord diagram. This diagram shows all the explicit internal references between chapters within ACI 318-14. Arrows point from the source provision to the target provision (colors have no meaning and are simply provided for clarity). Counts with no arrows (blank peripheral blocks) represent self-references within the chapter. Circled inset is ACI 318-11 Chapter 13 (Figure 3.1), which is comparable to ACI 318-14 Chapter 8 in function.

The massive and thorough reorganization effort, estimated at 150,000 work hours (100,000 hours contributed by volunteer committee members and 50,000 hours attributed to ACI staff), revealed many overlaps and gaps among ACI 318-11 provisions (Wood 2014). ACI 318-11 provisions were included verbatim in the ACI 318-14 revision to the extent possible, but some new language was developed to address those identified gaps. In addition to navigation improvements, the committee prioritized clarity in the document by replacing ambiguous words and phrases, deleting duplicate requirements, and including figures, tables, and equations instead of text where possible. To assist with the transition from ACI 318-11 to ACI 318-14, a transition keys (ACI 2014b, ACI 2014c) were produced, which mapped ACI 318-11 to ACI 318-14 and vice versa, respectively. The key mapping only the 2011 to 2014 version ran 79 pages.

ACI 318-14 has been since superseded by ACI 318-19 and ACI 318-22, which maintain the reorganized format and introduced color (in 2019) as a navigational aid as well as to make many figures easier to interpret. Now that the reorganized ACI 318 is established, this study reports a survey of user perception regarding whether the 2014 reorganization provided a more efficient design standard.

This background illustrates a very deliberate attempt to make ACI 318 more usable for practitioners although this was done in an almost entirely ad-hoc fashion. The committee drafting the document organized the new standard as they envisioned the design process required. The range of stakeholders on the committee, however, was not inclusive.

3.2 Survey Methodology

An anonymous online survey of concrete practitioners, intended to gather user sentiment and better understand the efficacy of the ACI 318 reorganization efforts, was conducted between February 21 and May 1, 2021. The survey was designed to determine which qualities of the standard were affected by the reorganization and to what extent user perception of complexity in the document changed. The survey consisted of several parts: questions gathering anonymous user information (demographic), Likert-style questions for each document (rating), Likert-style questions with documents at either extreme (head-to-head), ranking of general design standard qualities (ranking), and open-ended questions. The complete text of the survey is reported in Appendix A.

3.3 Survey Respondents

Seventy-four respondents participated, although not every question received an equal number of responses. In the description of results, both the total number of responses received to an *individual question*, which is the sample size n (i.e., $n \leq 74$), and the percentage of *those n respondents to the individual question* are reported. The reported percentages for each question will sum to 100% when rounded although the sample size varies from question to question. The breakdown of respondent experience (Figure 3.3) and the number of responses per question indicate a nonresponse bias that suggests that statistics from this survey may not provide valid approximations of the population of ACI 318 users.

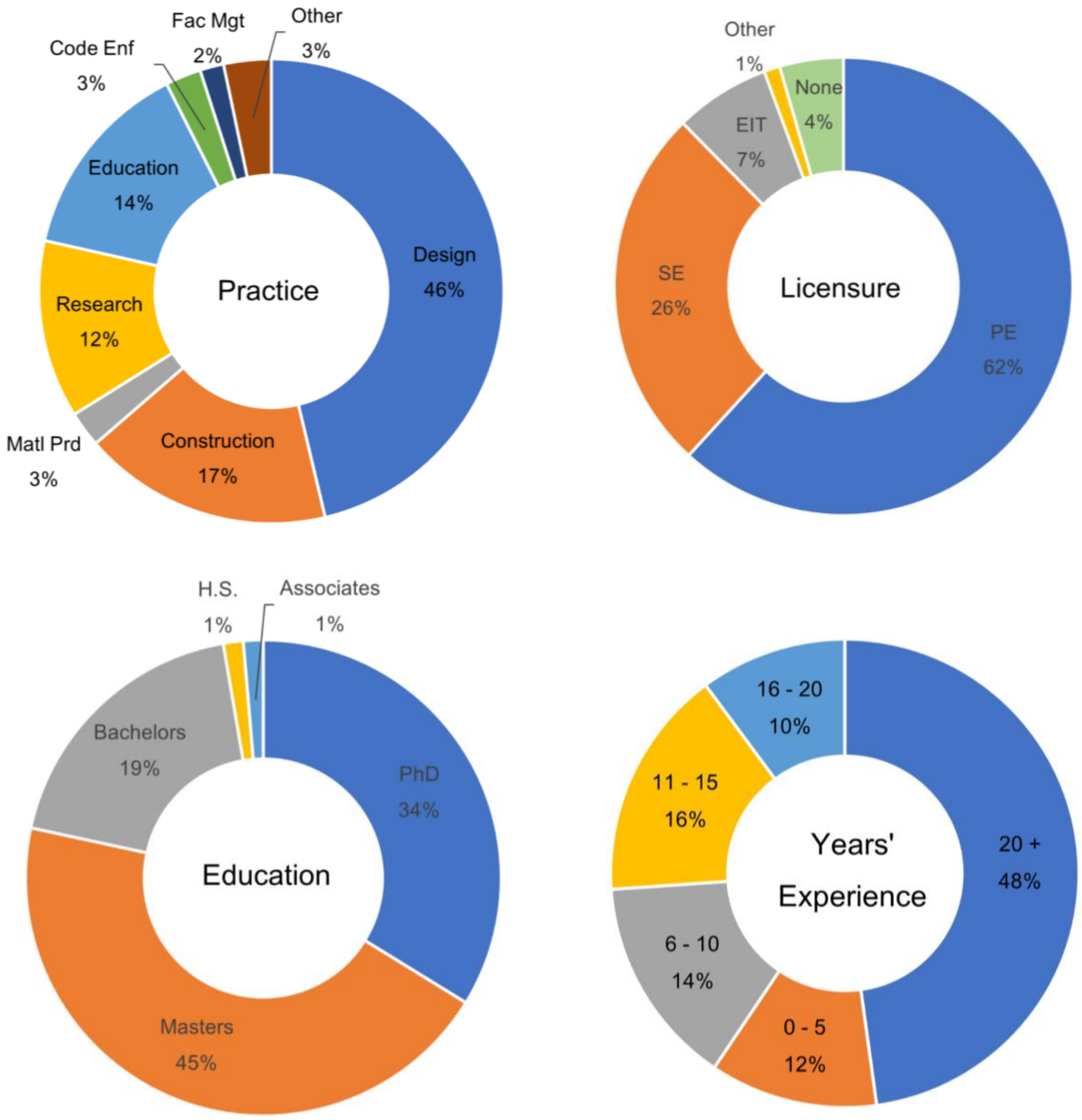


Figure 3.3 Demographic descriptions of respondents.

The majority (51%; 31 of 61 responses received) of respondents reported 8 or more years of experience using ACI 318-11, while most (61%; 36 of 59) reported 4 or more years of experience using ACI 318-14. Only 44% (30 of 69) of respondents said their practice involved seismic work. With ACI 318-14, 59% (35 of 59) of respondents use a print version of the publication, while 66% (40 of 61) reported typically using a print version of ACI 318-11. Over the course of a typical project requiring ACI 318, 25% of respondents consulted the document a few times a month, 39% consulted the document a few times a week, 17% consulted daily, and 17% reported consulting the document multiple times a day (n = 64). Respondents estimated that they relied on ACI 318, on average, 71% (49 of 69) of the time to ensure concrete design requirements were satisfied. Additionally, respondents were asked to use a sliding scale to indicate what level of confidence (%) they had in themselves and in the “average user” to correctly interpret and use each version of the standard (Figure 3.4). Respondents ranked their own abilities as being better than those of the average user and ranked their overall confidence in interpreting ACI 318-11 marginally better than ACI 318-14.

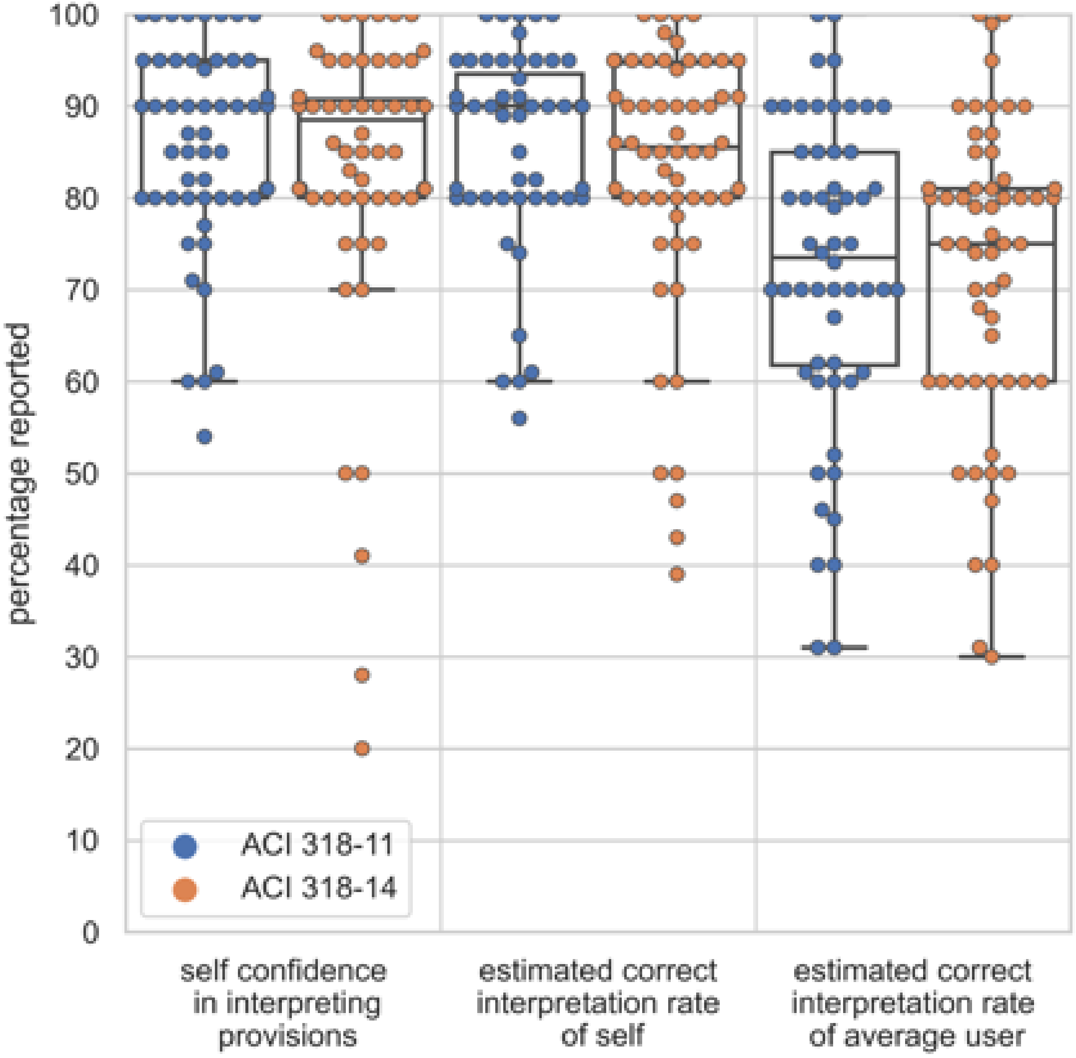


Figure 3.4 Confidence in the interpretation of ACI 318. Boxes indicate quartiles; outliers are beyond whiskers extended to 1.5 the interquartile range.

3.4 Ranking Important Qualities of a Standard

Respondents were asked to rank-order a total of 17 qualities of a design standard from 1 to 7 (1 was most important; 7 is least) according to their perceived importance to the success of the standard. The selection of qualities for ranking was guided by the conclusions of Angelino (2019) as discussed in Section 2.3.3. The majority of respondents indicated that the reorganization of ACI 318 successfully improved the qualities of the document that are most important to them. Respondents indicated that a logically presented standard (ranked second only after providing safe designs) where users can quickly identify (ranked 7), locate (ranked 6), and understand required provisions (ranked 4 and 5) was highly desirable (Figure 3.5).

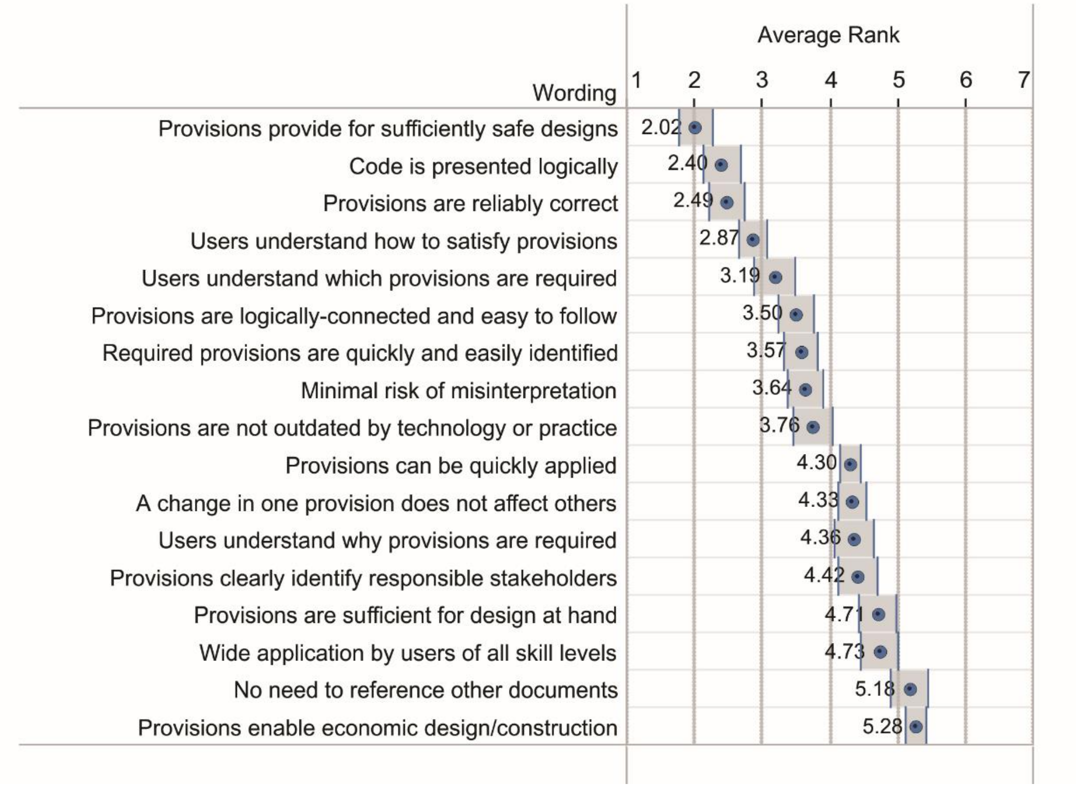


Figure 3.5 Relative rankings of 17 general qualities of a standard (n = 42). The average score (1 being the most important and 7 the least) for each quality is indicated with error bars showing estimated standard error.

When compared head-to-head, ACI 318-14 outperformed ACI 318-11 in these quality dimensions and almost all others (Figure 3.6). Respondents preferred ACI 318-11 over ACI 318-14 only when considering conciseness: "provisions are succinctly written," although the relative importance of this quality was not directly investigated in this survey. Neutrality on some head-to-head questions, such as those regarding the use of first principles and missing provisions, may indicate no change to these qualities was perceived by respondents, which aligns with the nature of the reorganization that intentionally avoided significant technical revision.

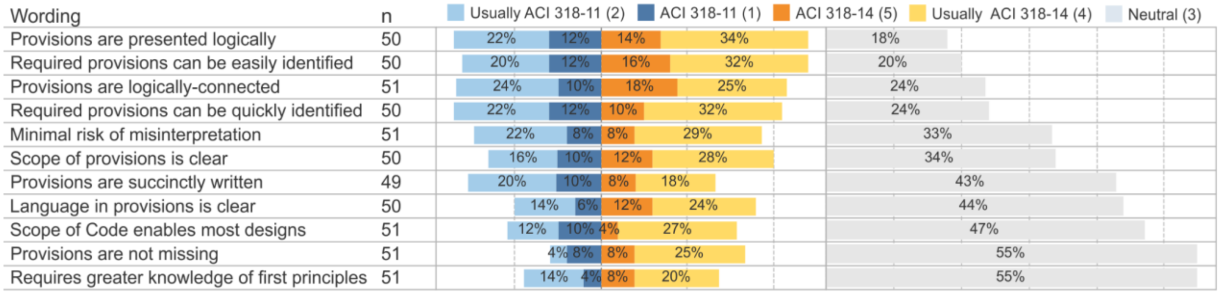


Figure 3.6 Head to head results are shown sorted top to bottom from least neutral response to most neutral response**.** Respondents were given the prompt: *"Please indicate which edition of ACI 318 better meets the following requirements: [wording shown left of figure]".* Respondents show preference for ACI 318-14 in nearly all cases.

Respondents were asked to rate each version of ACI 318 individually based on 10 quality dimensions (Figure 3.7). The results of that series of questions alone suggest that ACI 318-11 was an easier-to-use document. However, these results may be biased by the disproportionate representation of users with 20 or more years of experience (Figure 3.3) and the impassioned responses from some individuals. Respondents who preferred ACI 318-11 overall were more likely to select extreme or passionate choices ("Easy" for ACI 318-11 and "Difficult" for ACI 318-14) in the rating question set than those who indicated an overall preference for ACI 318-14. Interestingly, this pattern reverses in the head-to-head questions (Figure 3.6), with those who preferred ACI 318-11 overall showing higher rates of neutral responses and those with a preference for ACI 318-14 more likely to select an extreme choice. Engineers with 20 or more years of experience show greater positive response rates than those with fewer years of practice; a subset of three quality dimensions separated by users' experience is presented in Figure 3.8. The more positive view may be attributed to more experienced users being less dependent on the standard document itself in executing their work. One respondent appears to confirm this and the value of the more intuitive organization of ACI 318-14:

> "*After almost 40 years with the old organization of 318-11, I had the location of everything most common to my designs memorized. However, I find the new organization better, and my younger staff follows it better*."

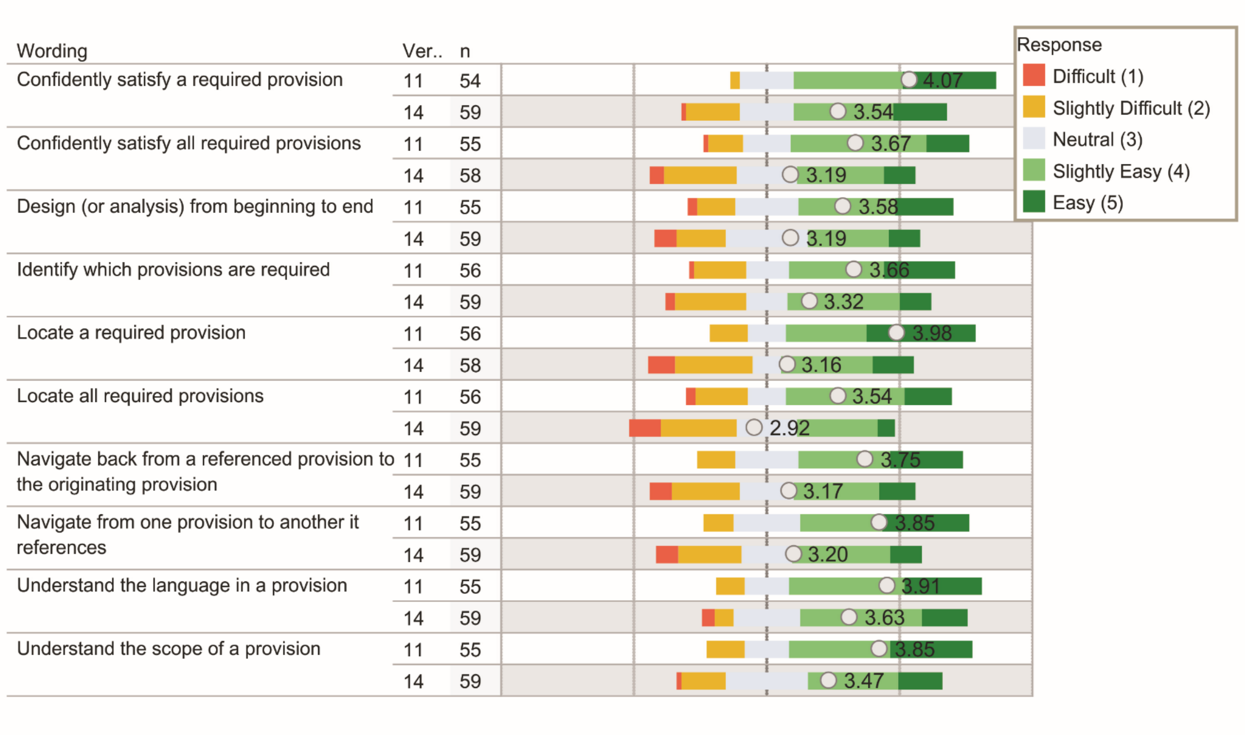


Figure 3.7 Rating results for each version of ACI 318. Response bars are centered about the neutral responses. The average response for each question is labeled and indicated by the white dot.

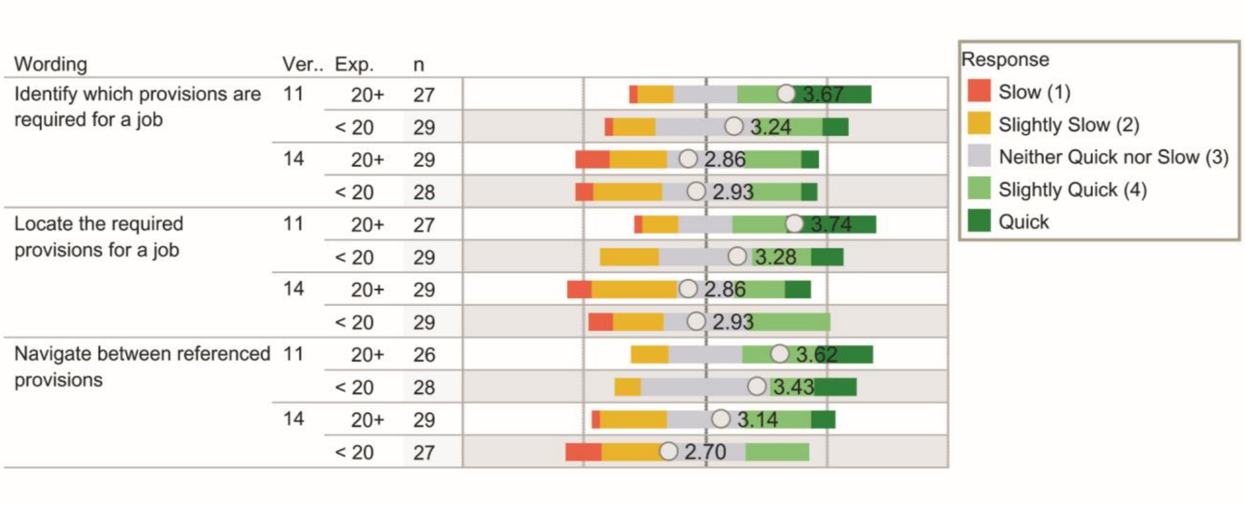


Figure 3.8 Speed of navigation rating results broken out by version of ACI 318 and years of experience. Response bars are centered about the neutral responses. The average response is indicated by the dot.

3.5 Conclusions from Survey

The results of this survey are somewhat contradictory. In terms of perceived ease of use, data shown in Figure 3.7 and Figure 3.8 appear to indicate a preference for ACI 318-11 although this may be biased by some extreme responses and the relatively large number of respondents having 20 years or more design experience (Figure 3.3). In head-to-head results, however, ACI 318-14 appears to outperform ACI 318-11 (Figure 3.6), particularly in the traits respondents identify as most important to a successful standard document (Figure 3.5). An interesting finding related to conducting both the independent ease-of-use portion and the head-to-head portion of the survey is the seeming incongruence between the results. It appears that head-to-head questions are more likely to receive objective responses from users, while independent inquiries allow subjective responses by passionate individuals to dominate the results. On average respondents thought average users would be more likely to correctly interpret ACI 318-14 than ACI 318-11, while the opposite was true for themselves (Figure 3.4). Figure 3.9 summarizes the average head-to-head results from all eleven questions asked (shown in Figure 3.6). The slight favor toward ACI 318-14 is apparent.

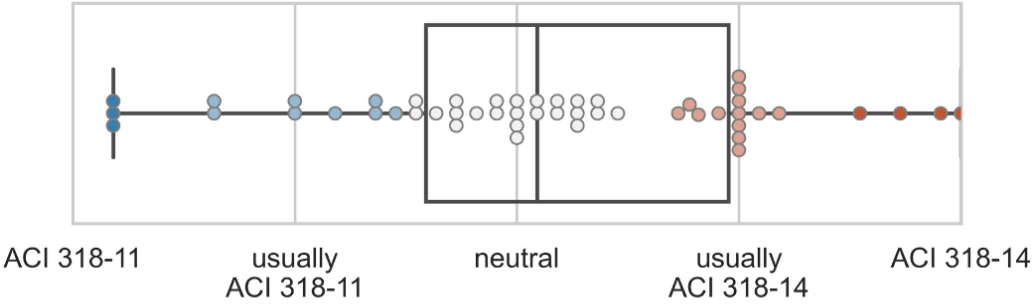


Figure 3.9 Average head-to-head results (summary of data in Figure 3.6). Each data point is one respondent. Boxes indicate quartiles, while whiskers extend to 1.5 the interquartile range, here encompassing all the data.

The response of one respondent having experience with both versions of ACI 318 perhaps sums up the survey best:

> *"A lot of the efficiency in engineering requires knowing where to find the right reference. The restructuring..., although much more logical, negated my ease of finding the required provisions based on all my previous years of experience. I feel that to use ACI 318 in the first place, a certain amount of knowledge is required. Expecting a code to be a 'cookbook' or a 'manual' is not a practical expectation."*

ACI has continued to improve the usability of ACI 318-19 by adding color and new diagrams as well as deep interactive links in the online version, ACI 318 PLUS. As support and features for application-based formats of design standards continue to grow, gathering user experience will become both easier and more useful. This new approach has the potential to completely change the way users interact with the standard by offering streamlined workflows and flattening the standard navigation learning curve. Furthermore, the document could be presented in entirely unique ways based on the particular stakeholder, their experience level, or the task at hand (automating a workflow or design flowchart as a series of bookmarks, for example).

Alternative presentations may include a machine-readable format for easy integration with digital design or compliance checking technologies. The full implications of these opportunities are yet to be explored by SWB and the larger design community. Nonetheless, monitoring and improving the user experience can guide and increase the smooth adoption of these new features and formats, ultimately ensuring that investments in standards become fully realized.

3.6 Chapter Summary

A survey conducted to aggregate experiences of end-users familiar with the flagship concrete design standard, ACI 318, found that that the general traits of standards that are most important to users were also the traits that users perceived as improved in the revision of ACI 318 between the 2011 and 2014 editions. The revision somewhat isolates the rectification of navigational complexity since it consisted primarily of a ‘structural’ reorganization with minimal changes to the technical content of the standard. Respondent perceptions of the standard before and after the revision are mixed and likely skewed against the revision due to the sample’s longer tenure of design experience respondents. Statistically significant conclusions about the population of users cannot be drawn from this survey due to the small sample size and unrepresentative demographics. Still, the results from this survey indicate the revision resulted in perceived improvements to particular traits of the standard that respondents found important. The seemingly incongruent results of the two portions of this survey also highlights the need to mitigate the effects of user bias and subjective experiences when surveying users. The survey results also align with

ACI's stated intention of the revision, to improve the ease-of-use of the standard via alignment with the design process (Poston 2009). Understanding how these two versions of ACI 318 compare to each other from the user's perspective is useful in the next chapter of the dissertation, where structural features of the documents alone are potentially ambiguous with respect to positive or negative outcomes.

4.0 Topological Analysis of Design Standards

The structure and presentation of design standards to end users has some obvious yet unmeasured effect on both the end-users' ability to accomplish their objectives in using the standard and for the standard to accomplish the objectives of its authors. Navigational complexity does not share a linear relationship with the number of provisions or the number of pages in a standard, but other metrics remain elusive and under investigated. As discussed in Section 2.4.1.2, Nyman (1974) developed reference networks for the 1969 AISC Specification and was able to identify logical loops and other structural issues within the standard. Developing and analyzing the network at that time was an immense undertaking. Advances in NLP, network computation, and hardware make this a compelling time to revisit these methods to explore structural complexity in design standards.

A graphical or network representation is a well-founded means of abstracting a standard in order to study its organization and structure. The reference network is admittedly simplified and will not capture all the relationships between datums within each provision. However, the reference network is easily enhanced and expanded with both more granular information and higher-level metainformation. Additional semantic representations of the provisions can be layered into the network to develop a refined sense of the relations within the document.

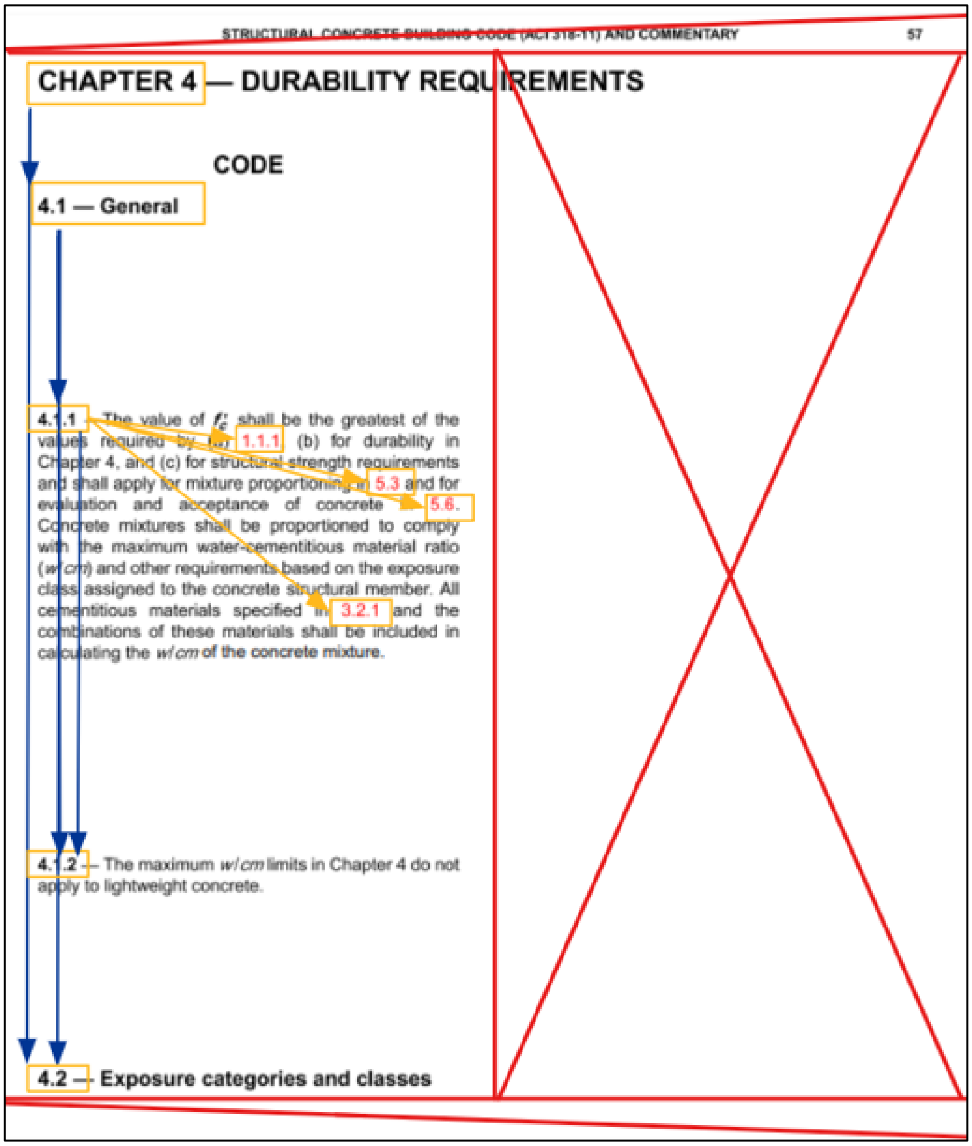
ACI 318 was selected for the reasons described in Section 3.1, namely the standard's ubiquity and 2014 re-organization following years of ad-hoc expansion. The survey described in Chapter 3 was conducted in order to develop some measure of the end-users' perceptions of complexity before and after the ACI 318-11 to ACI 318-14 reorganization. The results of the survey indicate that the respondents believe 'logical presentation' and other qualities related to navigation are important to the quality of standard documents. Respondents, on average, also believe that ACI 318-14 outperforms ACI 318-11 with respect to these qualities. These results align with ACI's documented effort to improve the standard. Therefore, here, the assumption that ACI 318-14 is a structurally improved standard over ACI 318-11 is adopted as a hypothesis.

In this chapter, characterizations and comparisons of the reference networks of each of the 2011 and 2014 versions of ACI 318 are presented. Useful metrics of navigational complexity may be identified by linking the end-users' aggregate experiences to the structures of the standards. First, the process of extracting the reference network from the standards' texts is discussed. Next, the features of those networks are explored: general characteristics, centrality metrics, degree assortativity[†], clustering and recurring motifs, and geodesic paths. Then, each network is enriched with semantic embeddings for each provision to investigate relations between structural features and meaning. This allows an inquiry into whether provisions that are semantically similar are closer in the reference networks, for instance. Finally, a summary of the findings and limitations of this analysis is presented.

4.1 Generating Graphs

Directed graph, or digraph, representations of ACI 318-11 and ACI 318-14 were developed based on their provisions and the references between them, respectively represented as nodes and directed edges. Edges are directed when the link operates in only one direction, such as a provisional reference, which cannot be traced backwards. References were considered either, explicit or implicit (shown schematically in Figure 4.1), based on whether a provision explicitly references another (yellow arrows in Figure 4.1 and yellow edges in Figure 4.2) or whether the nodes are hierarchically sequential (blue arrows and edges), respectively. The implicit network is sequential, following the table of contents at each hierarchical level and is meant to be somewhat representative of a natural ‘flow’ through the standard by the user. The reference network is assumed to be a directed graph, since referenced provisions will not point back to the initiating provision. A small portion of the resulting reference network of ACI 318-11, corresponding to the example page shown in Figure 4.1, is shown in Figure 4.2.

Only the standards’ provisions are considered in this analysis. As shown in Figure 4.1, PDF versions of the pages of the documents were cropped to remove the commentary and other extraneous text (headers and footers). The initial chapters, which contain few references or are glossaries, were also excluded from analysis. When the early chapters were included, particularly Chapter 1, the regular expression pattern matching algorithm matches on many false positives (Type I error) throughout the document. Examples include confusing load and resistance factors (i.e., “1.1”, “1.25”, etc.) with references to Chapter 1. References to outside codes, standards, or other documents were also excluded from the analysis. The set of nodes in the implicit networks were verified ‘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. The set of edges in the explicit network was developed by text extraction, described in the next section, and were not strictly validated. Known Type II errors occur from grouping sections or chapters (e.g., “Chapters 1 – 4”, will only return “Chapter 1” as an explicit reference). Type I errors may still occur in similar situations as described above.



STRUCTURAL CONCRETE BUILDING CODE (ACI 318-11) AND COMMENTARY 57

CHAPTER 4 — DURABILITY REQUIREMENTS

CODE

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 4.1 Psuedo-processing of a page in ACI 318-11. PDF pages were cropped to remove extraneous text (red areas). Note this page has no parrallel commentary and partially cropped chapter titles had to be added manually after text extraction. Blue arrows indicate the implicit references gathered from the text, yellow arrows indicate the explicit references. Each type of reference is represented by the corresponding color in a snapshot of the network in Figure 4.2.

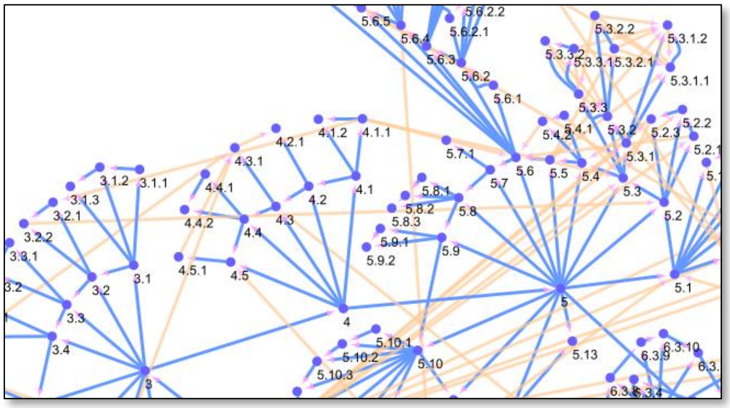


Figure 4.2 Portion of ACI 318-11 reference network showing Chapter 4. Blue and yellow edges represent implicit and explicit references, respectively. Direction is indicated by pink arrowheads.

4.1.1 Text Processing

The ACI 318-11 and ACI 318-14 documents were obtained in Adobe Portable Document Format (PDF). PDF files are a proprietary rich document format, allowing hyperlinks, digital signatures, layered objects, and embedment of forms, tables, images, or videos. These enhancements and their associated metadata can be useful to the user and the creator but are challenging for text processing. To extract the text from the documents, the Python[10] package PyMuPDF[11] was used to first crop pages to eliminate the adjacent commentary, headers, and footers (Figure 4.1). Tables and charts were identified and excluded from analysis utilizing algorithmically detected bounding boxes. The remaining text was extracted to a simple format (plain text file) and cleaned to a uniform state (i.e., consistent new line characters between each provision) using substitutions facilitated by regular expressions.

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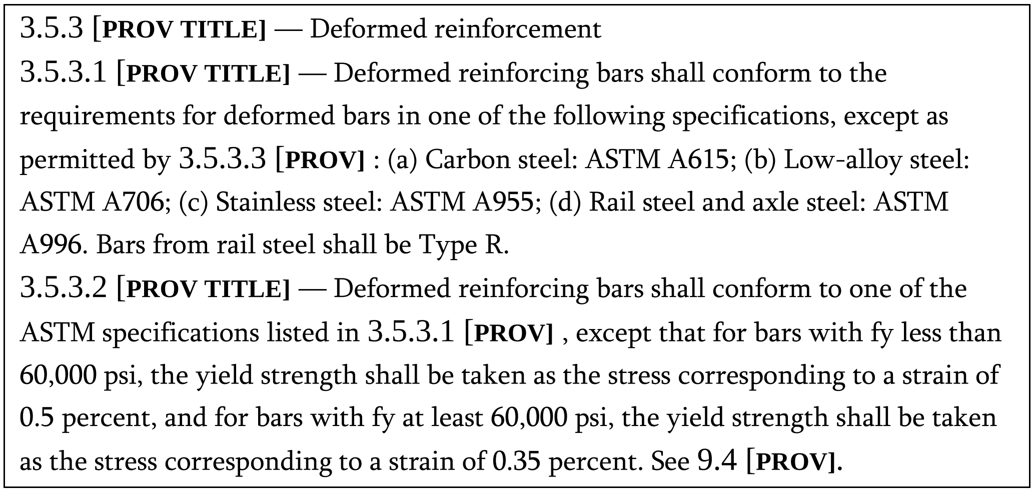
[10] Version 3.8

[11] Version 1.21.1

Low-level text processing was undertaken using the spaCy[12] package in Python. Chapter titles, provision titles, and explicit references to internal provisions were identified and labeled using regular expressions pattern matching. Shown in Figure 4.3 is an output showing the token labels [bracketed] of interest from processing an excerpt of ACI 318-11.



3.5.3 [**PROV TITLE**] — Deformed reinforcement
3.5.3.1 [**PROV TITLE**] — Deformed reinforcing bars shall conform to the requirements for deformed bars in one of the following specifications, except as permitted by 3.5.3.3 [**PROV**] : (a) Carbon steel: ASTM A615; (b) Low-alloy steel: ASTM A706; (c) Stainless steel: ASTM A955; (d) Rail steel and axle steel: ASTM A996. Bars from rail steel shall be Type R.
3.5.3.2 [**PROV TITLE**] — Deformed reinforcing bars shall conform to one of the ASTM specifications listed in 3.5.3.1 [**PROV**] , except that for bars with fy less than 60,000 psi, the yield strength shall be taken as the stress corresponding to a strain of 0.5 percent, and for bars with fy at least 60,000 psi, the yield strength shall be taken as the stress corresponding to a strain of 0.35 percent. See 9.4 [**PROV**].

Figure 4.3 Excerpt from low-level processing of ACI 318-11.

Network graphs were created based on these labels, with each node representing a [PROV TITLE] and each explicit reference edge in the network representing the directed relationship between the initiating [PROV TITLE] and the [PROV] found within the provision. Neither of the ACI 318-11 or ACI 318-14 networks capture the co-occurrent relations between provisions that simply mention or require action on the same datum (i.e., a variable or general topic), although this should be explored in further research.

The complete reference networks for ACI 318-11 and ACI 318-14 are shown in Figure 4.3 and Figure 4.4, respectively. Each provision is represented by a colored node and each chapter is

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[12] Version 3.2.2

represented by a color to distinguish it from those next to it. The relative sizes of the chapters can be determined by inspection. Explicit and implicit references are not distinguished from one another, though nearly all chapter-to-chapter edges are explicit references which gives rudimentary insight into the density of references between some chapters.

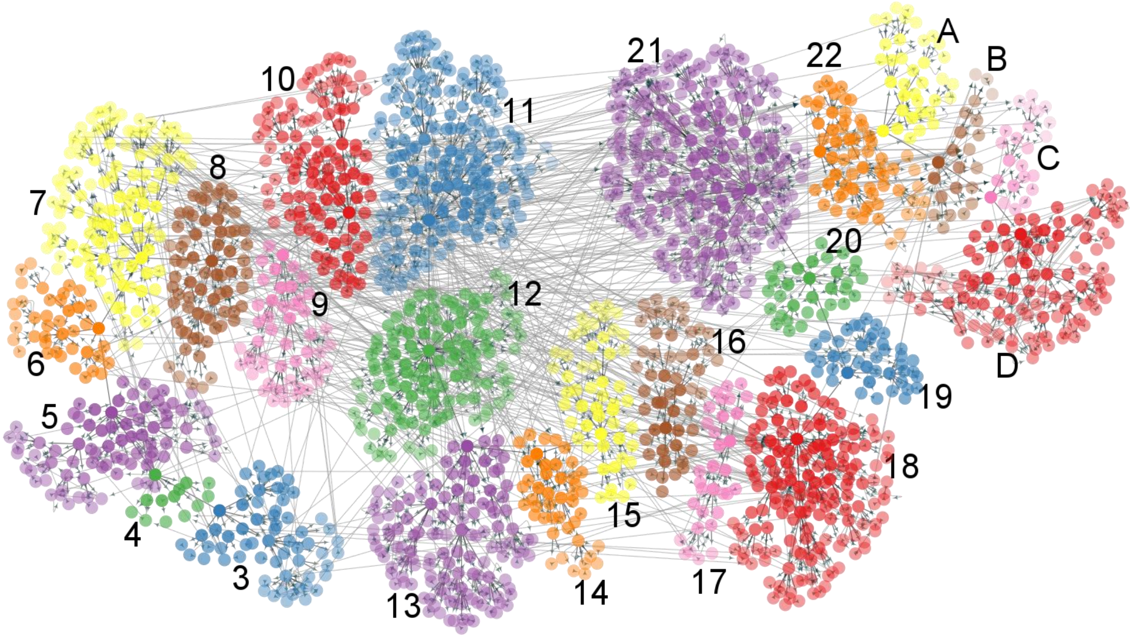


Figure 4.3 ACI 318-11 complete reference network. Chapters are labeled and colored only for clarity. Explicit and implicit references are represented by grey arrows. Nodes with greater translucency are deeper in the hierarchy. Layout is based on the implicit network.

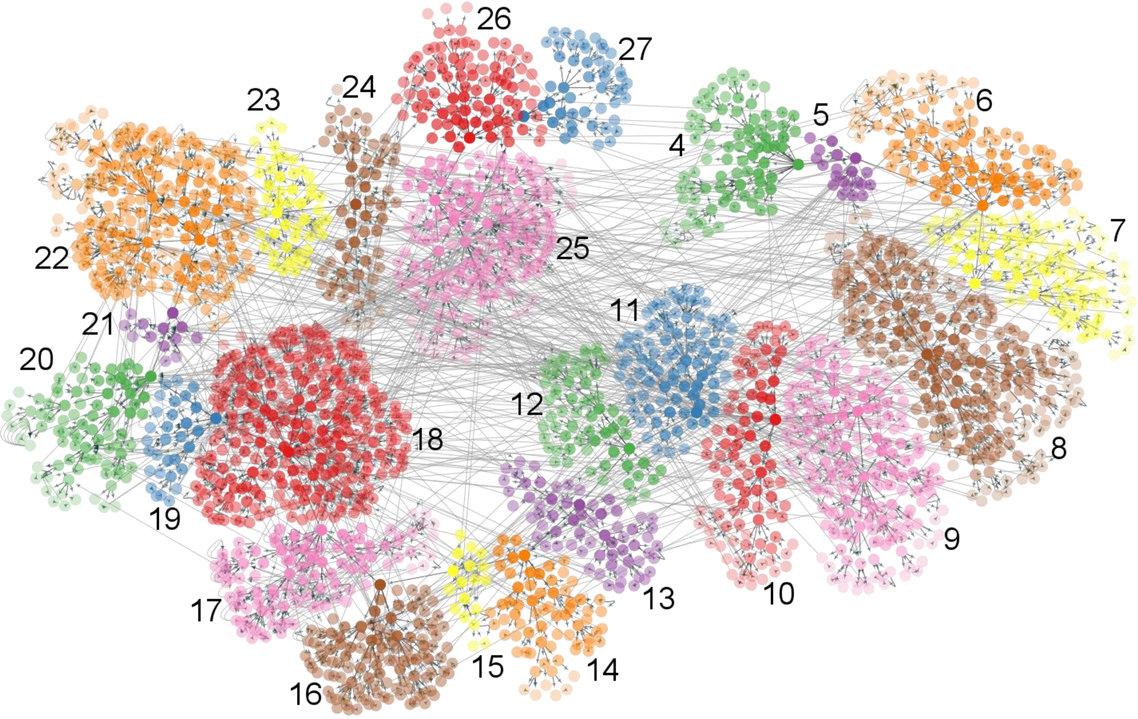


Figure 4.4 ACI 318-14 complete reference network. Chapters are labeled and colored only for clarity. Explicit and implicit references are represented by grey arrows. Nodes with greater translucency are deeper in the hierarchy. Layout is based on the implicit network.

4.2 Network Features

Graphs and networks are high-level abstractions and are therefore applicable across many fields of science and engineering. For this reason, there are many metrics that can be extracted from the network, although it is not immediately clear which may be related to navigational complexity. Here, centrality, clustering, and geodesic paths are used to explore the connectivity of ACI 318-11 and ACI 318-14. Implicit and complete reference networks are considered separately in order to understand effects of explicit references on connectivity in each of the networks. Table 4.1 summarizes the basic features of the networks of ACI 318-11 and ACI 318-14, as well as various connectivity features extracted; the latter are described in the following sections. Although ACI 318-14 increased in size both by number of nodes and edges, the number (and proportion) of explicit edges and nodes active in the explicit network are reduced. Similarly, although the lengths of both the characteristic path and diameter increase after the revision (indicators of increased connectivity), the largest strong component fraction decreases (indicator of decreased connectivity or modularity). By definition, all nodes of strongly components can reach each other, meaning that the revision has a nuanced effect on connectivity, likely preferential to one direction. In other words, end-users can potentially encounter longer paths through ACI 318-14, but they are typically directed ‘forwards’ (confirmed in 4.2.5) or ‘backwards’, while cyclic paths are more prevalent in ACI 318-11.

Table 4.1 ACI 318-11 and ACI 318-14 digraph feature summary

	ACI 318-11	**ACI 318-14**
Nodes	1876	2368
Edges	4638	5175
Implicit Edges (% of total edges)	3284 (71%)	3978 (77%)
Explicit Edges (% of total edges)	1354 (29%)	1197 (23%)
Explicit Direction (Forward: Backward)	(601:753)	(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 (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 C (mean/median)	0.274 / 0.166	0.245 / 0.333
Average Node Depth in Implicit Network	3.28	3.63
Pages in PDF	509	524

4.2.1 Centrality Metrics

The centrality of a node is a measure of its importance to the network. There are a variety of ways to measure centrality (Table 4.2), since there are many ways to define importance. Generally, centrality is calculated by counting paths containing each node, giving rise to two ‘flavors’ of centrality; radial and medial. Radial centralities, such as degree and eigenvector, count nodes on paths where the node being analyzed is the start or end of the path. Medial centralities, such as betweenness, consider the number of paths that pass through the node under analysis (typically including those beginning and ending at the node). Centralities typically consider either the volume or the length of the paths. Common means of calculating centrality are described in the following sections. Each centrality analysis described is presented with a distribution of the centrality metric across the networks as well as the 5 nodes rated as most central by the algorithms.

Table 4.2 Non-exhaustive taxonomy of centrality measures
(expanded from Borgatti and Everett 2006)

	Radial	**Medial**
Volume	**degree** degree-related: k-path status total effects Graph-theoretic Power Index **eigenvector** eigenvector-related: iterated standing power prestige Katz, **PageRank, HITS**	**betweenness** betweenness-related: flow betweenness k-betweenness mediative effects centrality random-walk betweenness rush
Length	**closeness** closeness-related: information intermediate effects	distance-weighted fragmentation reach

4.2.1.1 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 we characterize edges as incoming or outgoing (relative to a node) and describe this nodal metric as ‘in-degree’ or ‘ out-degree’, respectively. Three degree distributions are observed for directed graphs: the total-degree (Figure 4.5), in-degree (Figure 4.6), and out-degree (Figure 4.7) distributions. The distributions represent the probability, *P(k)*, that a node in the network is connected to *k* other nodes.

Global network properties such as scale-freeness are often determined by fitting the network’s degree distributions. Both ACI 318-11 ($\alpha = 0.388$) and ACI 318-14 ($\alpha = 0.394$) exhibit log-normal distributions with exponential decay parameters (α) decidedly non scale-free (Newman 2010). For networks where degrees are uncorrelated, i.e. when nodes have no affinity to connect with similar degree nodes, the statistical properties of the network are determined by the degree centrality (Boccaletti et.al 2006). Uncorrelated networks, which do not display degree assortativity or disassortativity[†], could be considered random (however, in Section 4.2.2 slight assortativity in ACI 318 in shown).

Much like the distributions in Figure 4.5, degree distributions in other real networks commonly skew right and demonstrate exponential decay as the degree increases (Newman 2010). Across all three distributions, ACI 318-14 has a slightly lower average degree compared with ACI 318-11, indicating fewer references per provision. The total-degree distribution shows a significant increase in leaf nodes from ACI 318-11 to ACI 318-14, which have in-degree of 1 and out-degree of 0. By the network definition (Section 4.1), 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 (e.g. ACI 318-11 section 5.7.1, shown in Figure 4.2). This trend between versions indicates increased modularity, which may serve as a requirement decoupling mechanism.

Table 4.3 shows the nodes with the greatest degrees in each of the standards. As one would expect, in the implicit networks these are simply the chapters with the most sections and subsections. In the complete networks there are a few provisions in each standard with large numbers of outgoing explicit references. These are atypical provisions that serve speacialized roles.

4.2.1.1.1 Example: Specialized Roles

Appendix B.1 in ACI 318-11 explains which provisions in the main document must be substituted with provisions in Appendix B if provision in the alternate design approach described in Appendix B is pursued. B.18.1.3, for instance, references an extensive list of provisions that 'shall not apply' when the alternate design approach is adopted. Similarly, in ACI 318-14, 18.2.1.6 references provisions necessary to satisfy special siesmic-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 indeed important for end-users. 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.

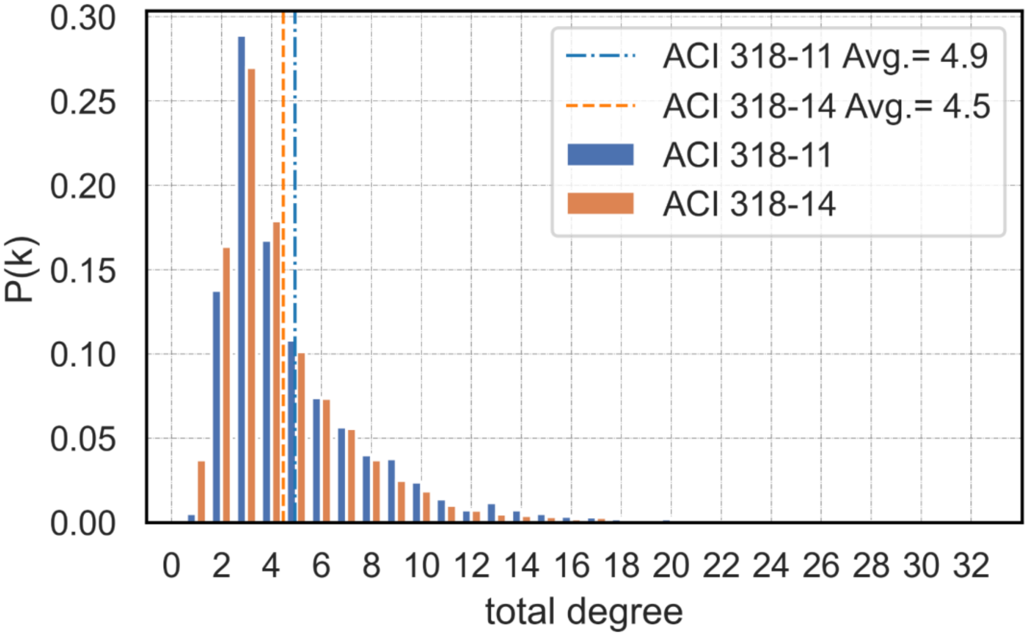


Figure 4.5 ACI 318 complete networks total-degree distributions.

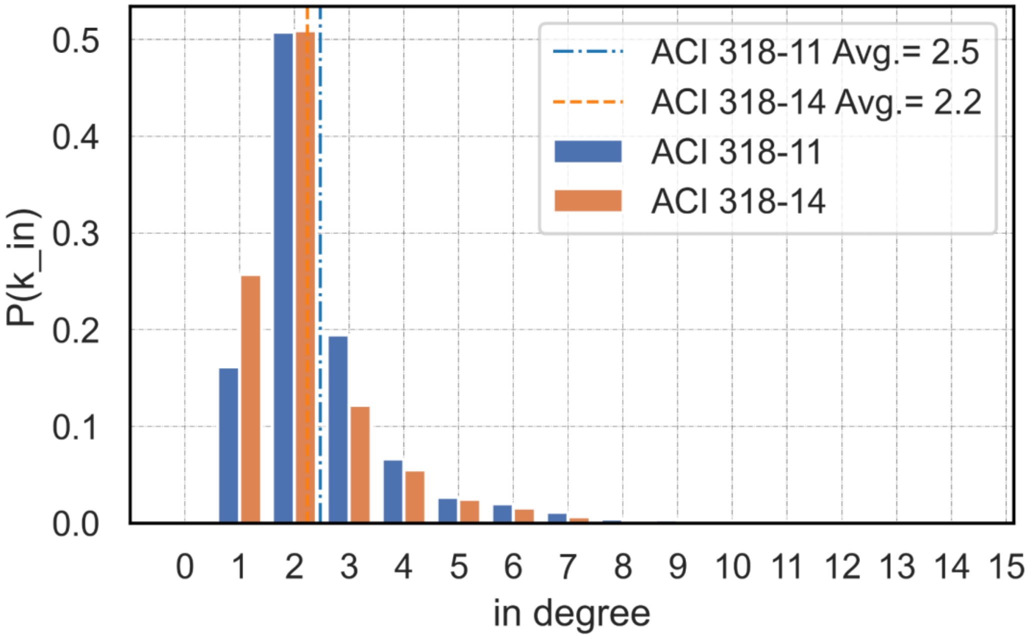


Figure 4.6 ACI 318 complete networks in-degree distributions.

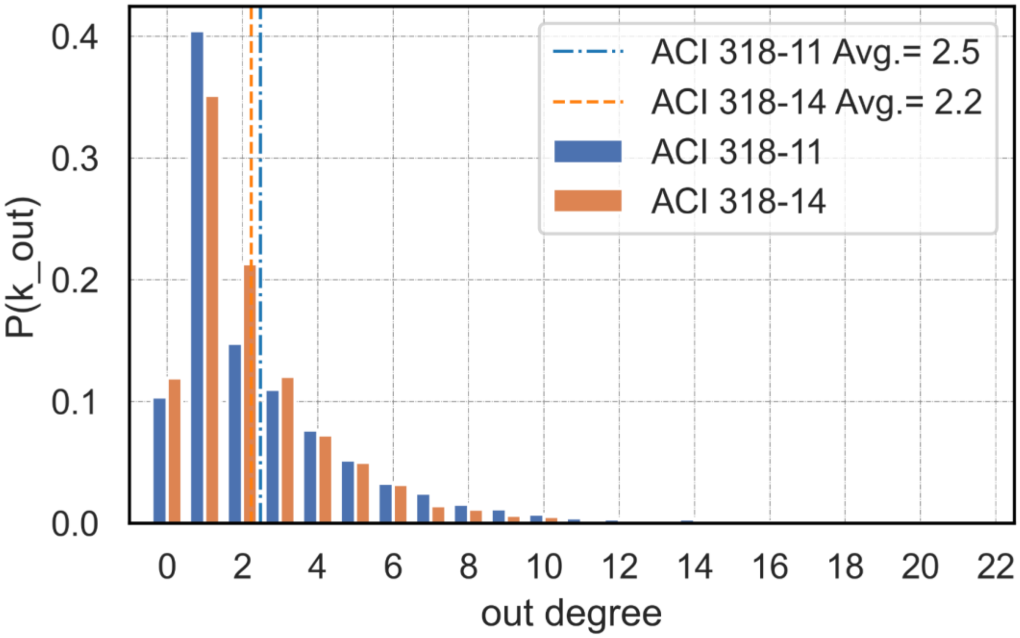


Figure 4.7 ACI 318 complete networks out-degree distributions. ACI 318-14 has a slightly smoother peak and reduces the proportion of nodes with out-degree 1.

Table 4.3 Top in and out-degree nodes (counts) for ACI 318-11 and ACI 318-14

	ACI 318-11 Implicit	**ACI 318-11 Complete**	**ACI 318-14 Implicit**	**ACI 318-14 Complete**
Total-degree	18 (24) 12 (21) 8 (16) 10 (16) 5 (15) 6.3 (15) 7 (15) 19.4 (15) 21 (15)	12 (34) 18 (28) B.1 (23) 10 (21) 9.2 (20) 11 (20) 14.3 (20) 21 (20)	18 (16) 4 (15) 26 (15) 5.3 (14) 18.12 (14) 22.6.9 (14)	18 (29) 6 (25) 18.2.1.6 (25) 25.4 (22) 22.5 (21)
in-degree	1406 tied at 2	12 (14) 21.6.4.2 (14) 4 (13) 9.2 (12) 14.3 (12)	1610 tied at 2	21.2 (16) 5 (15) 6 (15) 18 (14) 18.7.5.2 (13)
out-degree	18 (23) 12 (20) 10 (15) 8 (15) 5 (14)	18 (23) B.1 (22) 12 (20) 18.1.3 (16) B.18.1.3 (16)	4 (15) 18 (15) 26 (14) 5.3 (12) 8 (12)	18.2.1.6 (23) 4 (15) 18 (15) 17.3.1 (14) 26 (14)

4.2.1.2 PageRank Centrality

PageRank is a scoring algorithm developed by Google to rank search results that matched a user's query (Page et al. 1999). The algorithm is a natural extension of eigenvector and Katz centrality measures (Newman 2010). The premise of the PageRank, eigenvector, and Katz centrality metrics, which are radial and volume-based metrics, 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). Eigenvector centrality, which effectively counts paths of infinite length, is omitted due to the ACI 318 networks' cyclic nature. Katz centrality, a variant of eigenvector centrality, is omitted in favor of PageRank, which is similar but more discerning with high-centrality transfer between nodes (Newman 2010).

The PageRank centrality of each node *i*, is proportional to the sum its neighbors' scores divided by their out-degree. Formally,

$$C_{PR}(i) = \alpha \sum_{j} A_{ij} \left(\frac{C_{PR}(j)}{k_j^{out}} \right) + \beta_i \tag{4.1}$$

is the PageRank centrality for node *i*, where:

A is the adjacency matrix, whose elements are defined:

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

k^{out} is a node's out-degree. If a node has out-degree of zero, then $k^{out} = 1$ by convention. $A_{ij} = 0$ as well, so such a term does not contribute to the summation.

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

β is the rank source factor; $1/N$ was used here.

N is the number of nodes in the graph.

PageRank centrality distributions for the complete ACI 318-11 and ACI 318-14 networks are shown Figure 4.8. There is an increase of the proportion of nodes within the lowest bin of scores from ACI 318-11 to ACI 318-14, which is mostly due to the greater number of nodes in the ACI 318-14 network. Table 4.4 summarizes the top-ranked nodes as determined from PageRank centrality. Results cannot be described as 'important' or common to design instances.

Another way to interpret these results is via the 'random surfer model', where a user starts at a random location and 'surfs' the network edges (Page et al. 1998). PageRank results order nodes by their likelihood to be encountered on the model surfer's random walks through the network. To avoid becoming trapped in cycles within the network and 'becoming bored', at some point the surfer will randomly jump to another node in the network (this is implemented by the β parameter). The β parameter used here is uniformly distributed, but alternative implementations could give nodes higher on the hierarchy a higher starting rank, meaning a surfer will be more likely to jump to these nodes to start walks. Intuitively, this more closely mimics how a user is likely to use a standard. 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 (Richardson and Domingos 2001).

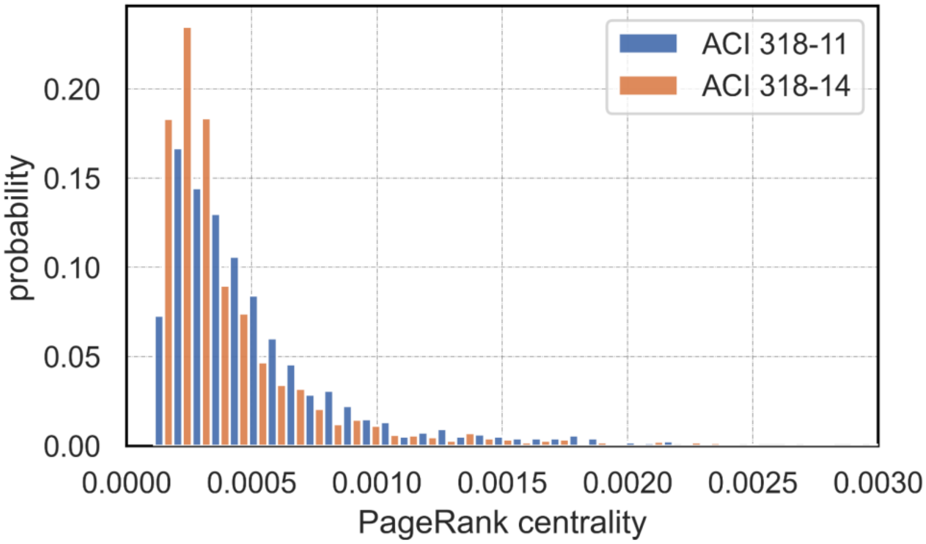


Figure 4.8 ACI 318 complete networks PageRank centrality (x-axis is truncated for clarity). The PageRank centrality of ACI 318-11 is more evenly distributed across the network than those of ACI 318-14. On average, nodes are more 'important' to the rest of the network before the revision.

Table 4.4 PageRank top nodes (scores) for ACI 318-11 and ACI 318-14

ACI 318-11 Implicit	ACI 318-11 Complete	ACI 318-14 Implicit	ACI 318-14 Complete
11.9.9.5 (0.001500)	12.14.3.4 (0.005756)	7.7.3.8.4 (0.001231)	6.3.2.2 (0.004093)
3.5.3.11 (0.001429)	12.14.3.5 (0.005285)	9.7.3.8.4 (0.001230)	6.3.2.3 (0.003987)
7.10.4.9 (0.001403)	12 (0.005090)	24.2.3.9 (0.001144)	25.4.8.1 (0.003891)
10.2.7.3 (0.001354)	10.6.4 (0.004138)	20.2.1.7.3 (0.001142)	25.4.8.3 (0.003792)
7.10.4.8 (0.001334)	10.6.5 (0.003673)	22.5.10.5.6 (0.001136)	25.4.8.2 (0.003503)

4.2.1.3 HITS Centrality – Hubs and Authorities

One drawback with PageRank centrality is that it 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 at many nodes (Kleinberg 1999). 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 be both hubs and authorities and the best hubs identify where the best authorities can be found.

The authority centrality is defined as:

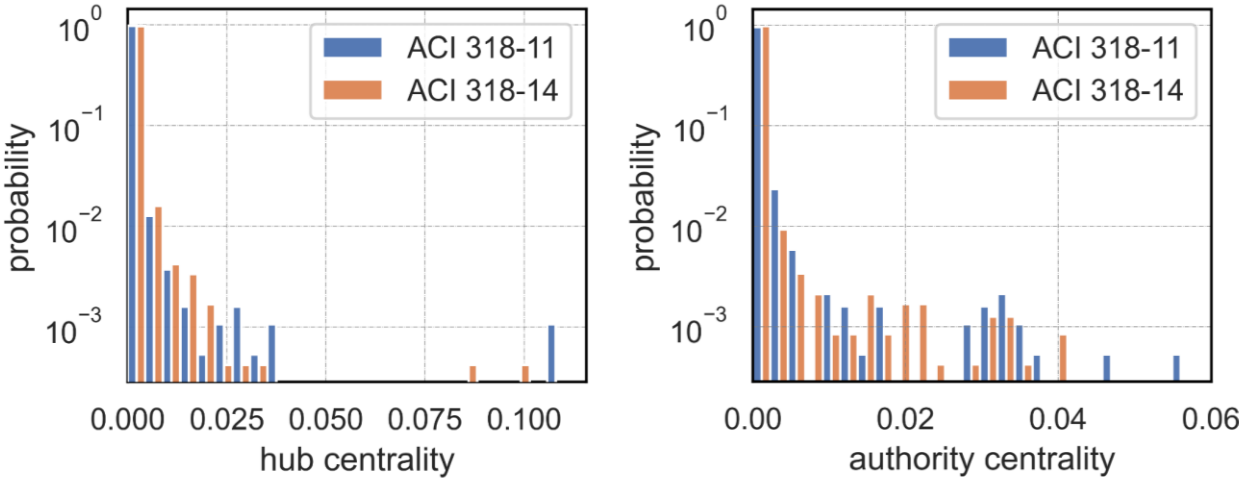
$$C_a(i) = \sum_j A_{ij} C_h(j) \tag{4.2}$$

Similarly, the hub centrality is defined as:

$$C_h(i) = \sum_j A_{ji}\, C_a(j) \tag{4.3}$$

Note that the adjacency matrix elements are index A_{ji} rather than A_{ij}, in Eq. 4.3, so that a hub (source) is defined by those nodes pointed to (targets).

The HITS hub and authority centralities for the complete networks are shown in Figure 4.9. Table 4.5 shows top hub 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 Figure 4.13e, located in Section 4.2.1.6), while ACI 318-14 appears to have only one major hotspot for each (Chapter 18 in Figure 4.14e, located in Section 4.2.1.6). The hotspot chapters in ACI 318-11 were some of the most heavily revised after 2011, 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 it is identifying atypical referencing between provisions, potentially highlighting areas that have special function but also those potentially in need of reorganization or revision.



a) hub centrality b) authority centrality

Figure 4.9 ACI 318 complete networks HITS centrality.

Table 4.5 Top hub and authority nodes (scores) for ACI 318-11 and ACI 318-14

	ACI 318-11 Implicit	ACI 318-11 Complete	ACI 318-14 Implicit	ACI 318-14 Complete
Hubs	18 (0.44) 18.12 (0.03) 18.13 (0.02) 18.2 (0.03) 18.3 (0.02)	B.18.1.3 (0.11) 18.1.3 (0.11) 14 (0.04) 14.4 (0.04) 10 (0.34)	18 (0.31) 18.12 (0.08) 18.10 (0.07) 18.2 (0.04) 18.7 (0.03)	18.2.1.6 (0.10) 18 (0.08) 18.2 (0.03) 18.2.1 (0.03) 18.7.5 (0.03)
Authorities	18.13 (0.04) 18.14(0.04) 18.3 (0.04) 18.4 (0.04) 18.19 (0.04)	14.3 (0.06) 14.5 (0.05) 13 (0.04) 10.5 (0.03) 18.13 (0.03)	18.13 (0.04) 18.11 (0.04) 18.3 (0.04) 18.8 (0.04) 18.7 (0.04)	18.6 (0.04) 18.8 (0.04) 18.10 (0.03) 18.3 (0.03) 18.11 (0.03)

Sample provisions demonstrating high Hub Centrality in the ACI 318-11 complete network include:

> *“14.4 — Walls designed as compression members*
> *Except as provided in 14.5, walls subject to axial load or combined flexure and axial load shall be designed as compression members in accordance with provisions of 10.2, 10.3, 10.10, 10.11, 10.14, 14.2, and 14.3.”*

and,

> *“B.18.1.3 - The following provisions of this Code shall not apply to prestressed concrete, except as specifically noted: Sections 6.4.4, 7.6.5, B.8.4, 8.12.2, 8.12.3, 8.12.4, 8.13, B.10.3.3, 10.5, 10.6, 10.9.1, and 10.9.2; Chapter 13; and Sections 14.3, 14.5, and 14.6.”*

4.2.1.4 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. In messaging or transit networks, nodes with high betweenness can be interpreted as being important intermediaries or as useful shortcuts to move between two other nodes. Nodes with high betweenness centrality may exert influence within a network through their control over information passing between other nodes (aka bottlenecks). 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 real-world scenarios, of course, not all nodes exchange communications with the same frequency. Considering a standard, in most cases, end-users do not take the geodesic path. Betweenness centrality, $C_B(i)$, of a node i is the sum of the fraction of all pairs of geodesic paths g_{st} that pass through node i.

Formally,

$$C_B(i) = \sum_{s \neq i \neq t} \frac{n_{st}^{i}}{g_{st}} \qquad (4.4)$$

is the node betweenness centrality for *i*, 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 $g_{st} = 0$.

If a user moves through the standard travelling only along geodesic paths, or along a random path amongst geodesic paths of the same length, then $C_B(i)$ is proportional to the average rate at which users encounter node *i*. Similar assumptions hold well for roadway or messaging traffic, but they may not hold or be relevent here. Regardless, the distributions for ACI 318-14 and ACI 318-14 complete networks are presented in Figure 4.10.

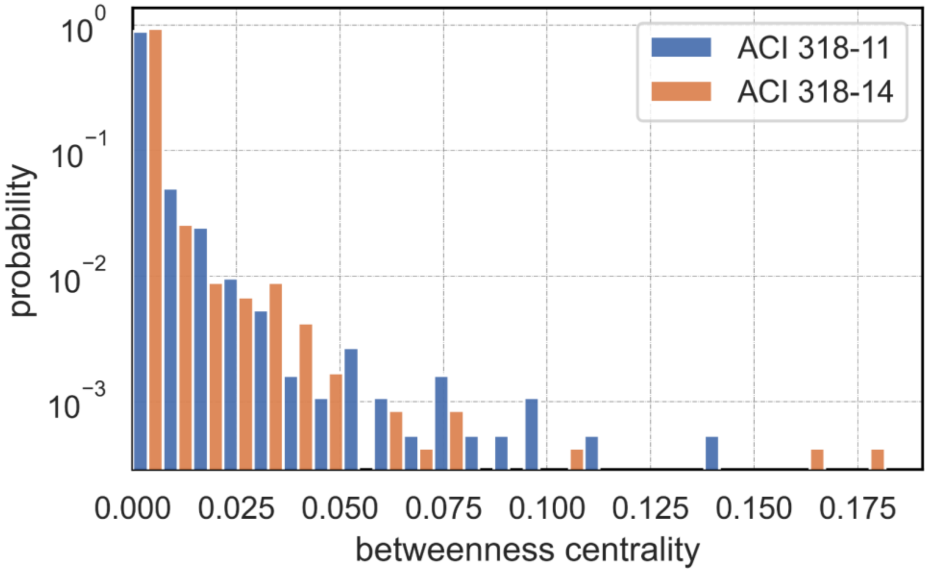


Figure 4.10 ACI 318 complete networks betweenness centrality.

Table 4.6 Betweenness top nodes (scores) for ACI 318-11 and ACI 318-14

ACI 318-11 Implicit	**ACI 318-11 Complete**	**ACI 318-14 Implicit**	**ACI 318-14 Complete**
11 (0.03)	12 (0.14)	16 (0.03)	6 (0.18)
18 (0.03)	13 (0.11)	17 (0.03)	7 (0.17)
12 (0.03)	11 (0.10)	18 (0.03)	8 (0.10)
17 (0.03)	B (0.10)	15 (0.02)	9 (0.08)
16 (0.03)	A (0.09)	14 (0.02)	23 (0.08)

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 (e.g. in ACI 318-14 there is a shift from nodes 16, 17, 18 to 6, 7, 8 evident in Table 4.6). It is unclear whether any of the high betweenness nodes should really be considered "more important" than other nodes. Chapter 12 of ACI 318-11, "Development and Splices of Reinforcement", and Chapter 6 of ACI 318-14, "Structural Analysis", both exhibiting the greatest betweenness values, are likely used directly or indirectly by designers on most projects. Betweenness centrality scores for individual nodes do not appear particularly useful for discerning nodes from each other within the top five nodes. However, the top ten is rounded out by provisions from Chapter 25 “Reinforcement Details”, showing that betweenness may be an indicator of provisions that applicable to many design aspects, in a well-organized standard.

4.2.1.5 Closeness Centrality

Closeness centrality is a medial-length measure of centrality based on the average length of geodesic paths to a node. Greater values of closeness indicate greater centrality, but closeness scores tend to bunch together (see score values in Table 4.7), since the range of geodesic paths in the network typically will not vary significantly. 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, of a node *i* is the reciprocal of the average geodesic path distance **to** *i* over all *n* reachable nodes. Formally:

$$C_c(i) = \frac{n_i - 1}{\sum_j d_{ij}} \qquad \textbf{(4.5)}$$

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

Table 4.7 Closeness top nodes (scores) for ACI 318-11 and ACI 318-14

ACI 318-11 Implicit	ACI 318-11 Complete	ACI 318-14 Implicit	ACI 318-14 Complete
10.13.8.7 (0.003)	12.13 (0.08)	9.7.7.6 (0.002)	19.2.4 (0.06)
11.9.9.5 (0.003)	12 (0.08)	22.6.9.12 (0.002)	25.7.2 (0.06)
11.11.4.10 (0.003)	8.6.1 (0.08)	9.7.3.8.4 (0.002)	6.7 (0.06)
10.13.8.6 (0.003)	12.2 (0.08)	22.6.9.11 (0.002)	25.7.3 (0.06)
11.4.7.9 (0.003)	13 (0.08)	9.7.6.4.4 (0.002)	25.5.7 (0.05)

Closeness centrality is sometimes criticized for not discriminating enough between nodes, creating bins instead of meaningful rankings (notice top 5 nodes reported in Table 4.7 are essentially tied in all networks). However, for both complete ACI 318-11 and ACI 318-14 networks, provisions that are important to design are represented in the top 5. Closeness may be a fair indicator of the relative importance of nodes after introducing explicit references.

Distributions for closeness centrality scores from implicit ACI 318-14 and ACI 318-11 networks are shown in Figure 4.11. The distribution for ACI 318-11 implicit network centrality is slightly flattened (kurtosis = -0.14, skewness = 0.03) and is shifted positively compared to that of the ACI 318-14 implicit network (kurtosis = -0.04 and skew = 0.281), which displays a slightly positive skew. Greater closeness centrality means a lower geodesic path distance between nodes. A positive skew could indicate nodes with specific intermediate or path-shortening roles. The effect of explicit references on the networks (Figure 4.12), shortens paths for ACI 318-11 (increasing centrality), while relatively less so in ACI 318-14, indicating compensation. High relative kurtosis in ACI 318-11 complete network (kurtosis = 6.01, skew = -0.062) versus ACI 318-14 (kurtosis = 3.00, skewness = 1.17) indicates many nodes with same level of access to the rest of the network. Based on this analysis it may be desirable for explicit references to have only some marginal effect on closeness centrality. Since closeness centrality scores are normally distributed (even when geodesic path lengths distributions have long tails [shown in Figure 4.29]), the mean closeness centrality score may be a fair indicator of the impact of explicit referencing on the implicit network.

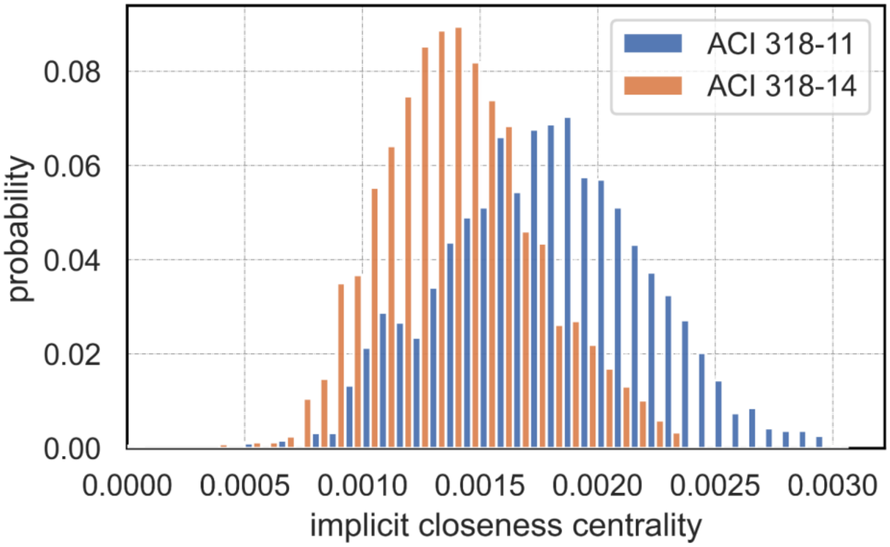


Figure 4.11 ACI 318 implicit networks closeness centrality distributions.
Mean: ACI 318-11 = 0.0018, ACI 318-14 = 0.0014.

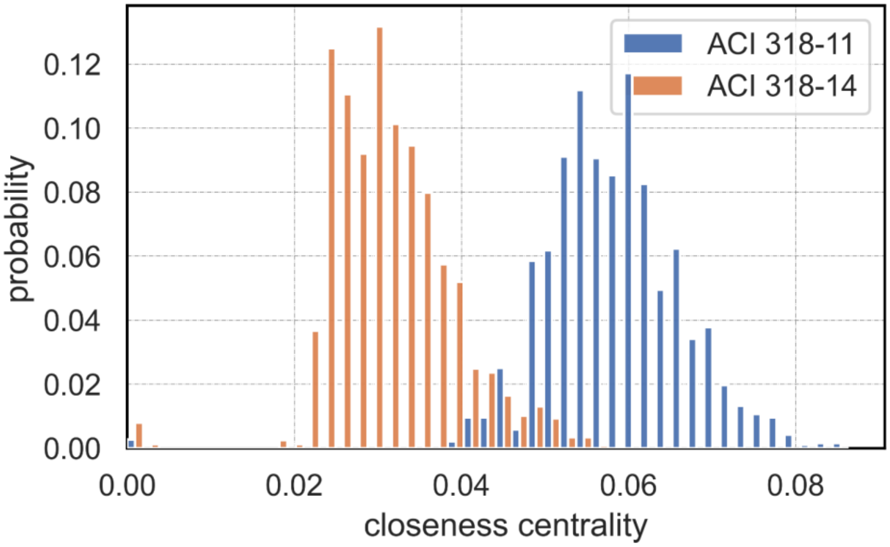


Figure 4.12 ACI 318 complete networks closeness centrality distributions.
Mean: ACI 318-11 = 0.058, ACI 318-14 = 0.048.

4.2.1.6 Centrality Summary

The centrality metrics presented in the previous sections provide useful insights into the structure of standard reference networks. A summary of these findings is presented below and tabulated in Table 4.8. Deviations from mean centrality scores for ACI 318-11 and ACI 318-14 networks are visualized in Figure 4.13 and Figure 4.14, respectively.

Table 4.8 Utility of centrality metrics to building design standards

	Radial	**Medial**
Volume	**degree**: potentially identifies specialized provisions with high importance. **PageRank:** potentially discerning of important information authorities **HITS:** sensitive to atypical referencing, potentially indicating areas of need or important provisions.	**betweenness:** scores could indicate nodes applicable to many design instances.
Length	**closeness:** may successfully rank important provisions in complete networks references.	

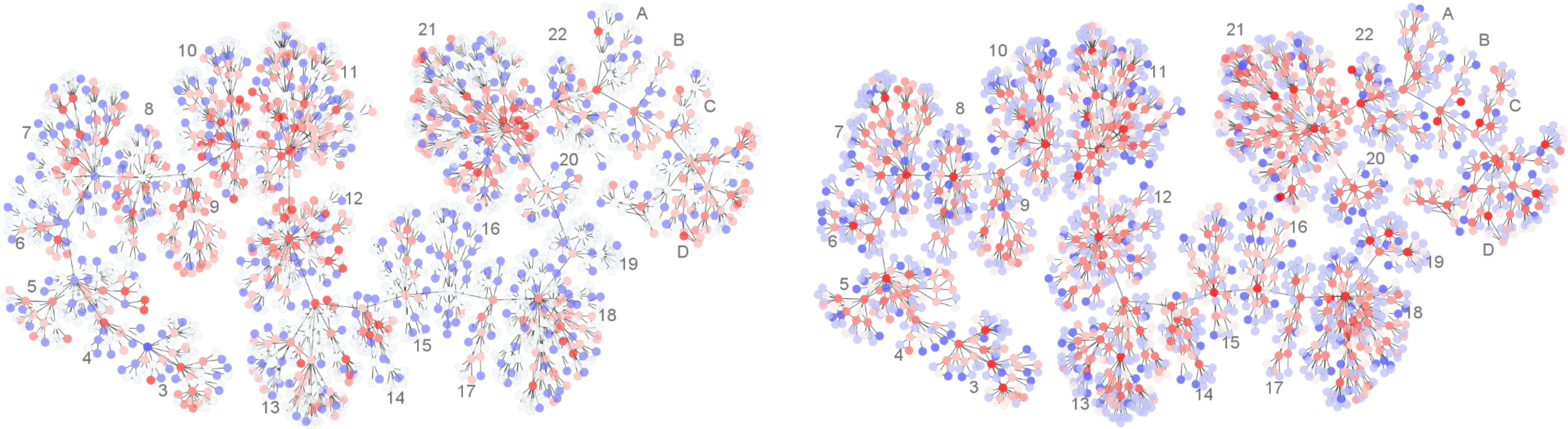
High degree centrality potentially indicates atypical provisions that serve specialized roles in the complete networks. Considering degree as a measure of centrality, those nodes with a relatively large number of explicit references are important for end-users but likely indicate areas of the network that lack robustness and would potentially benefit from SWB attention.

PageRank is a scoring algorithm developed by Google to rank search results based on the importance of the pages that link to them. The PageRank algorithm is a natural extension of eigenvector and Katz centrality measures. 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.

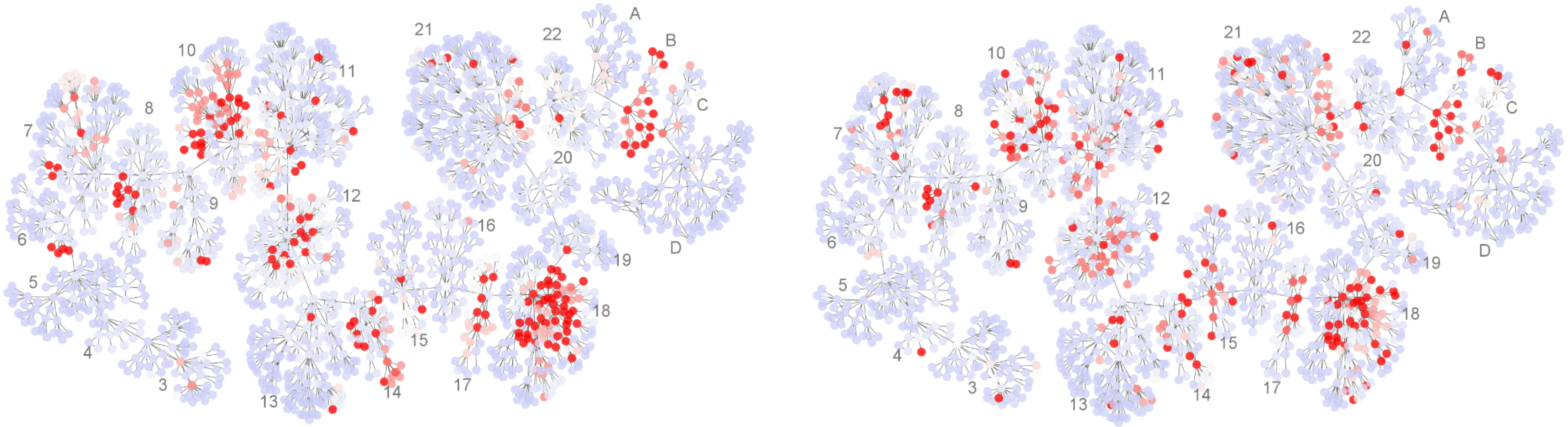
HITS scores are very sensitive to atypical referencing in the complete networks studied here and therefore seem to identify clusters of nodes in need of reorganization or revision (Figure 4.13). In a reference network with consistent referencing and structure, these scores may indicate hub and authority nodes important to user navigation (Figure 4.14 and Figure 4.14).

Betweenness centrality is a metric of centrality that measures the fraction of geodesic paths that pass through a node, indicating its importance as an intermediary or bottleneck in information flow. High betweenness nodes are critical to the network's overall functioning, and their removal can significantly disrupt flow. Explicit references have a significant impact on betweenness centrality, shifting high scores from nodes near the center to the outskirts. However, it is unclear if high betweenness nodes should be considered more important than others. While individual node scores may not be useful for discerning nodes from each other, betweenness centrality can be an indicator of provisions that are applicable to many design aspects.

Closeness centrality measures the average length of geodesic paths to a node, with higher scores indicating greater centrality. However, scores tend to bunch together, making it less discriminating between nodes. Nonetheless, nodes important to design received high scores when explicit references were introduced. The distributions of closeness centrality scores in ACI 318-11 and ACI 318-14 implicit networks differ slightly, with ACI 318-11 having a slightly flattened distribution and ACI 318-14 showing a slightly positive skew. Explicit references shorten paths and increase centrality in ACI 318-11, possibly indicating compensation over a poor implicit structure. The normally distributed scores suggest that the change in mean score can indicate the impact of explicit referencing on the implicit network.



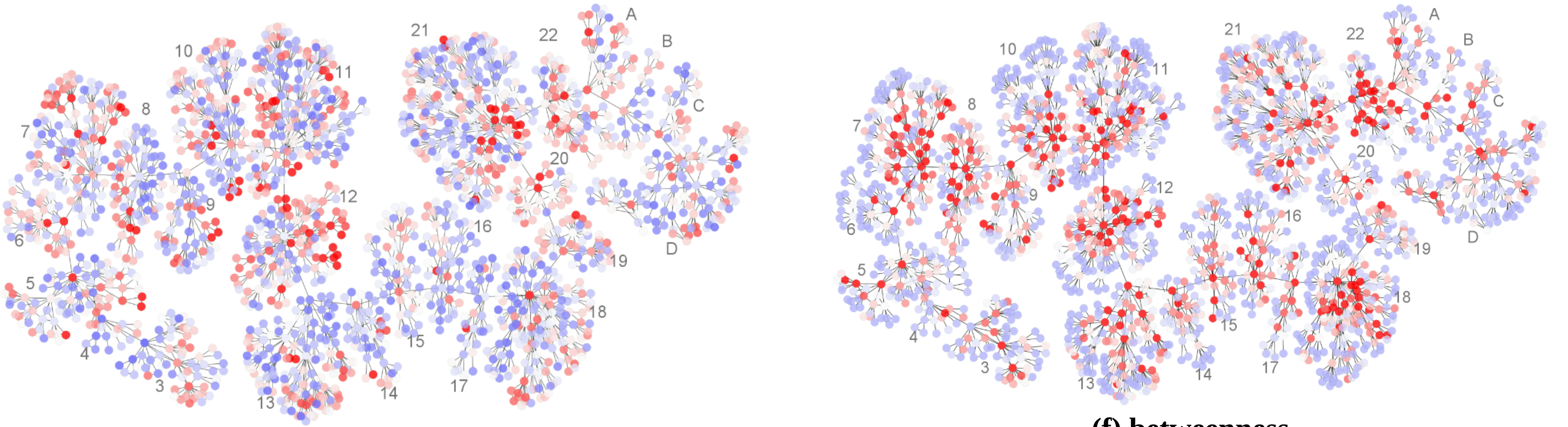
(a) in-degree **(b) out-degree**



(c) authority **(d) hub**

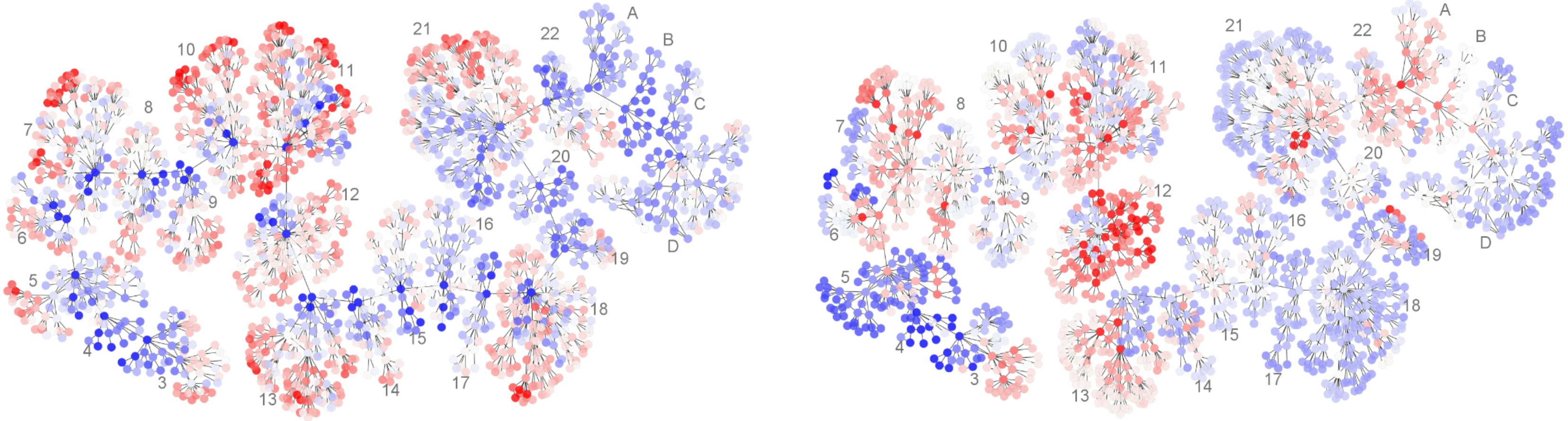
standard deviations from mean: -2≤ -1 0 1 ≥2

Figure 4.13 Summary of ACI 318-11 centralities (part 1). Explicit references are not shown. Where necessary, distributions were made normal-like using the Box-Cox transformation.



(e) PageRank

(f) betweenness



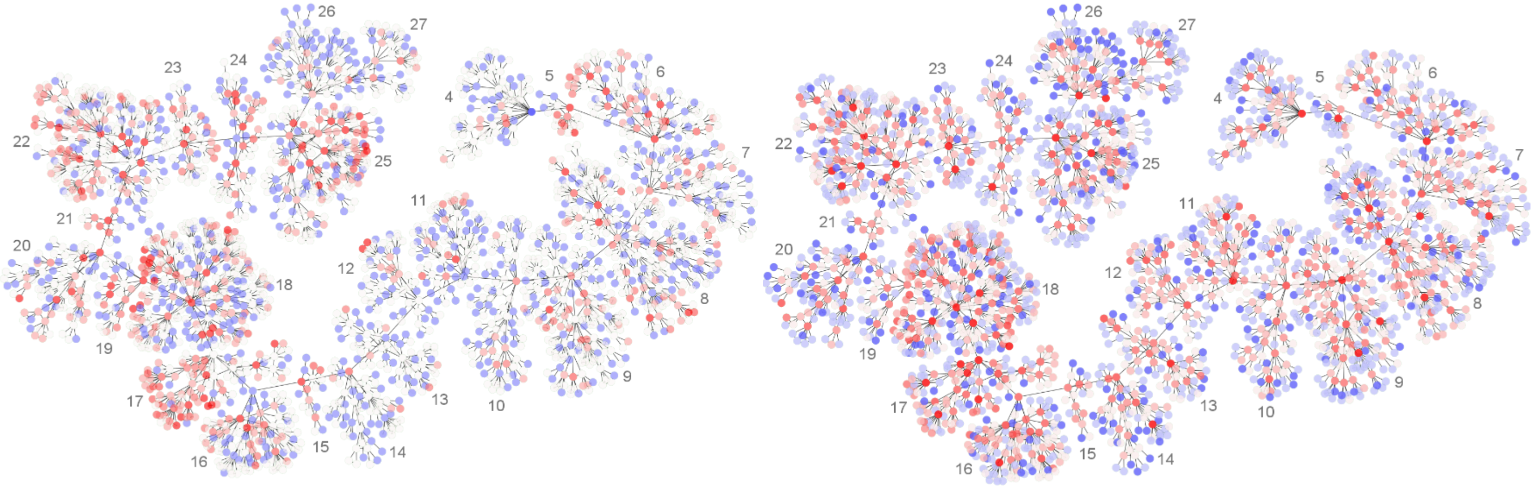
(g) closeness (implicit)

(h) closeness (complete)

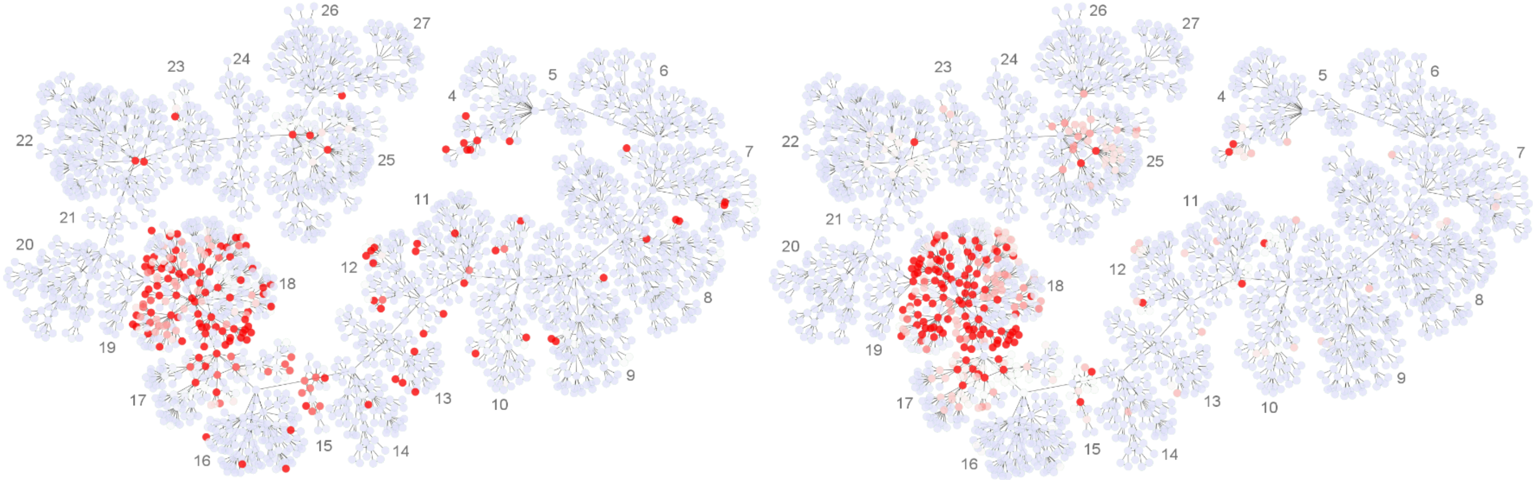
standard deviations from mean:

-2≤ -1 0 1 ≥2

Figure 4.13 Summary of ACI 318-11 centralities (part 2). Explicit references are not shown. Where necessary, distributions were made normal-like using the Box-Cox transformation.



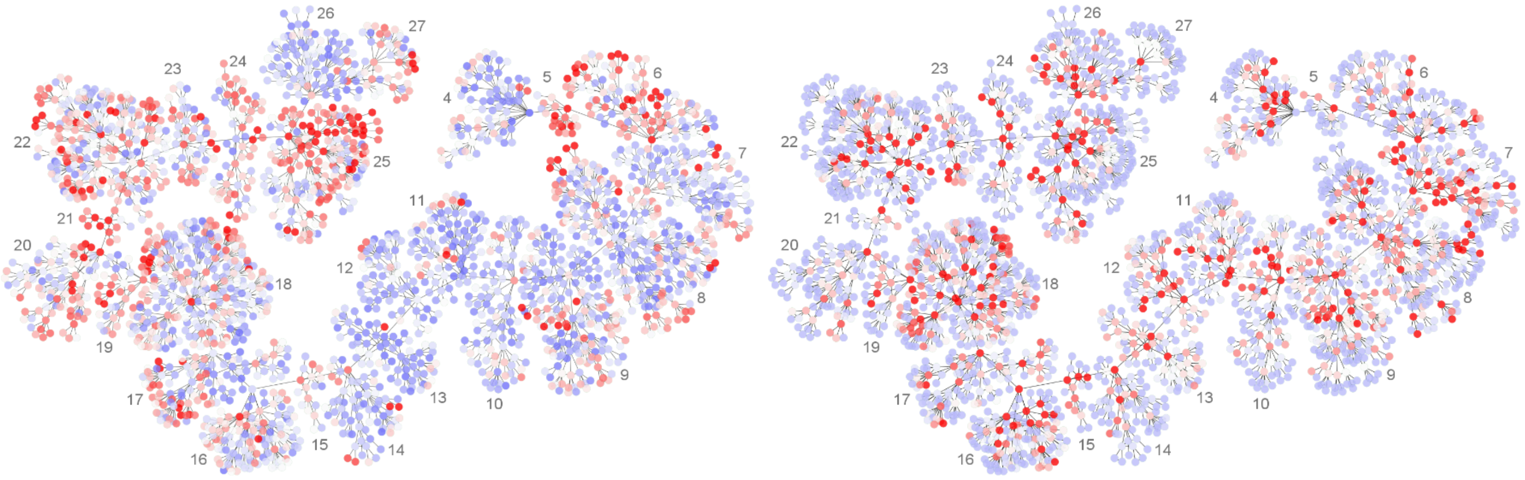
(a) in-degree **(b) out-degree**



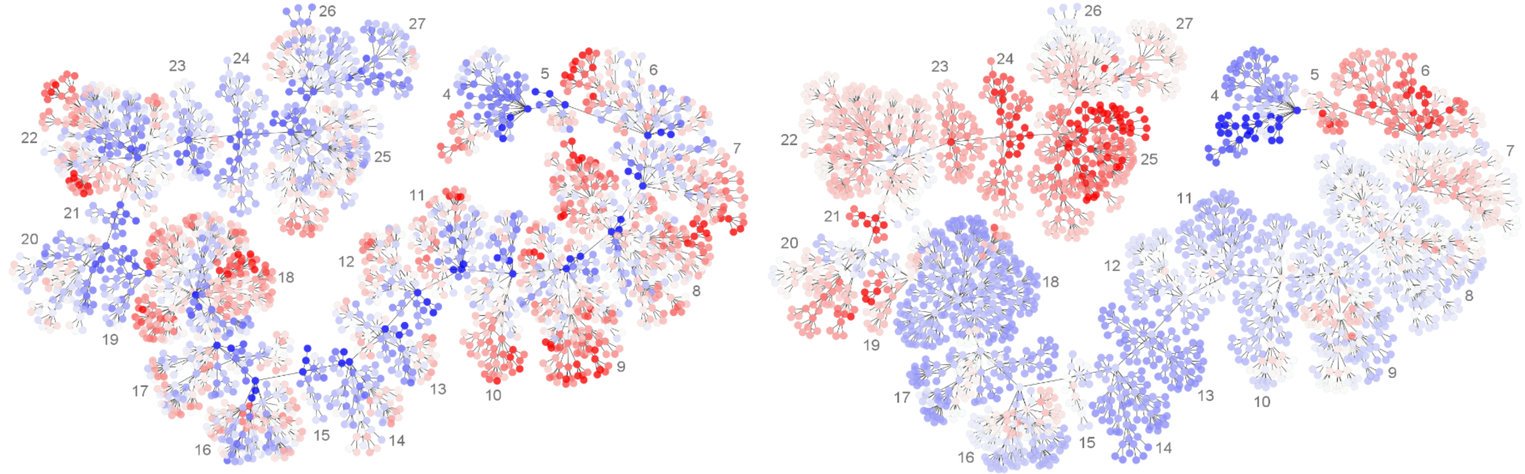
(c) hub centrality **(d) authority**

standard deviations from mean: -2≤ -1 0 1 ≥2

Figure 4.14 Summary of ACI 318-14 centralities (part 1). Explicit references are not shown. Where necessary, distributions were made normal-like using the Box-Cox transformation.



(e) PageRank **(f) betweenness**



(g) closeness (implicit) **(h) closeness (complete)**

standard deviations from mean:

-2≤ -1 0 1 ≥2

Figure 4.14 Summary of ACI 318-14 centralities (part 2). Explicit references are not shown. Where necessary, distributions were made normal-like using the Box-Cox transformation.

4.2.2 Degree Assortativity

Assortative mixing[†] is the tendency of nodes to connect strongly with others that have similar attributes, such as metadata (e.g., chapter, embedding) or node properties (e.g. centralities). In the study of social networks, assortativity is commonly referred to as homophily and is used to test the adage “birds of a feather flock together.” The simplest attribute of a node is degree of connectivity: the number of connections in or out of the node. The degree assortativity coefficient, r, for a network is defined as:

$$r = \frac{\sum_{ij}\left(A_{ij} - k_i k_j/2m\right)k_i k_j}{\sum_{ij}\left(k_i \delta_{ij} - k_i k_j/2m\right)k_i k_j} \qquad (4.6)$$

where m is the total number of edges,

δ_{ij} is the Kronecker delta function, which is 1 if $i = j$ and 0 otherwise.

The degree assortativity coefficient is in fact a Pearson correlation coefficient, ranging from -1 to 1 for which -1 indicates strong disassortativity, 0 indicates no correlation between connected nodes, and 1 indicates strong assortativity. Real world graphs typically lie between about -0.35 and +0.35. As shown schematically in Figure 4.15a, an assortative network has a dense core of highly connected nodes surrounded by tangential loosely connected nodes, known as a core/periphery structure. Whereas in a disassortative[†] network, shown schematically in Figure 4.15b, high degree nodes show preference for low degree nodes (and vice versa), which results in a more uniform appearance.

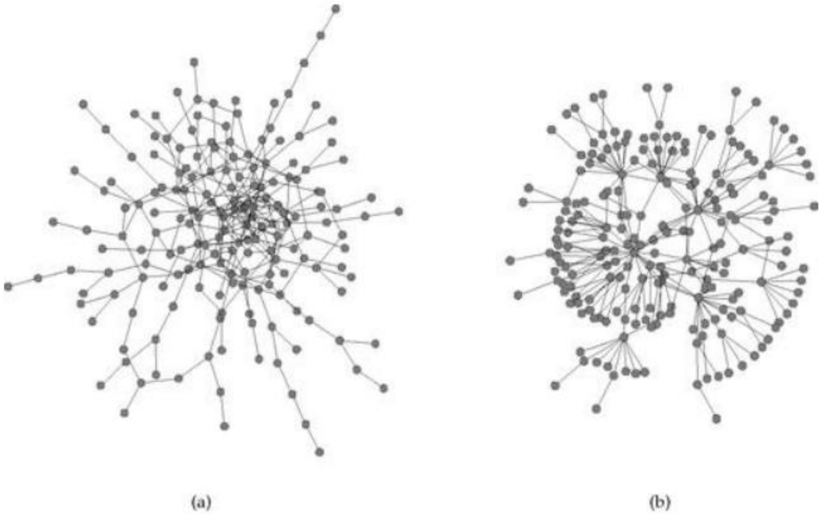


Figure 4.15: Degree assortative (a) and dissassortative (b) networks, where nodes with similar degree are respectively more likely or less likely to share an edge (Newman and Girvan 2003). Assortative networks display a core of high degree nodes, with low-degree peripheral nodes, while a disassortative network appears more uniform throughout.

Table 4.9 reports the degree assortativity for the implicit and complete reference networks for both ACI 318-11 and ACI 318-14. All networks tend toward being slightly assortative by degree while the explicit references decrease assortativity in ACI 318-14 and marginally so in ACI 318-11. This indicates that explicit edges have slight preference to link nodes with dissimilar degree. Nodes with similar degree are likely to share similar roles, such as those representing introductory provisions with many sub-sections or detailing provisions that have no sub-sections. According to Newman (2010), technical, information, and biological networks tend to be disassortative while social networks tend towards assortativity. This is thought to be due to the tight grouping in social networks, where members of a group all share a similar degree (by virtue of belonging to the same group). Assortativity can also be calculated based on node in/ out-degree, shown in Table 4.10 and Table 4.11, however many results show significant sensitivity using the jackknife error test.

Table 4.9 ACI 318 degree assortativity

Pearson correlation (jackknife error)

	ACI 318-11	ACI 318-14
Implicit	0.055 (0.042)	0.106 (0.044)
Complete	0.051 (0.033)	0.072 (0.048)

Table 4.10 ACI 318-11 in/ out-degree assortativity

Pearson correlation (jackknife error)

	Implicit		Complete		Difference	
S\T	**In**	**Out**	**In**	**Out**	**In**	**Out**
In	-0.018 (0.184)	-0.195 (0.071)	0.018 (0.042)	0.067 (0.042)	NSS	+ 0.26
Out	-0.058 (0.058)	0.343 (0.047)	-0.012 (0.043)	0.152 (0.032)	NSS	- 0.19
NSS = Not Statically Significant						

Table 4.11 ACI 318-14 in/ out-degree assortativity

Pearson correlation (jackknife error)

	Implicit		Complete		Difference	
S\T	**In**	**Out**	**In**	**Out**	**In**	**Out**
In	-0.042 (0.129)	-0.030 (0.093)	0.004 (0.034)	0.108 (0.034)	NSS	+
Out	-0.003 (0.047)	0.366 (0.045)	-0.061 (0.037)	0.152 (0.037)	NSS	- 0.21

4.2.3 Clustering and Motifs

The average clustering coefficient, *C*, is a global metric of a graph that reports the average probability that a node *k* shares edges with two nodes *i* and *j,* which already share an edge. This is sometimes called transitivity and it effectively measures the density of subgraph triangles in networks (Newman 2010). *C* is the network mean of clustering coefficient, $C_c(i)$, is the ratio of directed triangles of which node *i* is a part out of all possible directed triangles containing node *i*.

$$C_c(i) = \frac{T_i}{2(k_i(k_i - 1) - 2\mathrm{k}_i^{\leftrightarrow})} \quad (4.7)$$

is the clustering coefficient for node *i*, where:

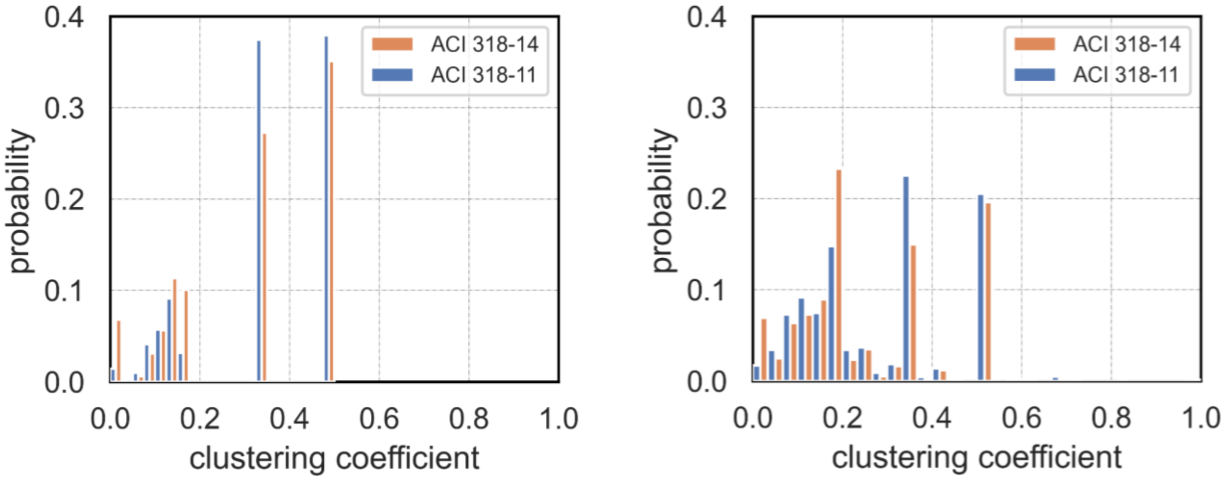
T_i is the total number of directed triangles through node *i*, equivalent to:

$$(A + A^T)^3_{ii}$$

k_i is the sum of in-degree and out-degree of node *i*,

$k_i^{\leftrightarrow}$ is the reciprocal degree of *i* equivalent to: A_{ii}^2.

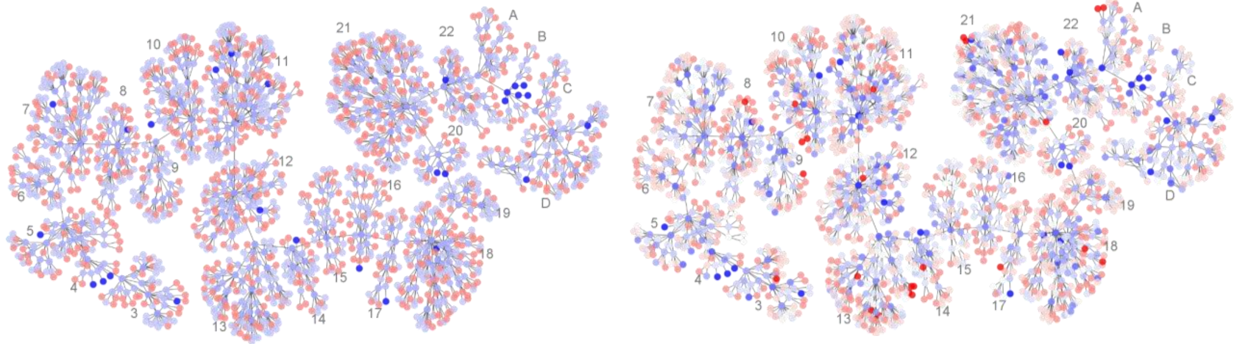
The distributions for clustering coefficients in ACI 318-11 and ACI 318-14's implicit and complete reference networks are shown in Figure 4.16. Deviations from the mean are visualized for both standards' implicit and complete reference networks in Figure 4.17. These two figures indicate that the ACI 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 clustering scores. Nodes with a zero score are typically subclauses deeper in the hierarchy and do not have preceding or succeeding provisions (i.e., these nodes have an in-degree of 1).



a) implicit network

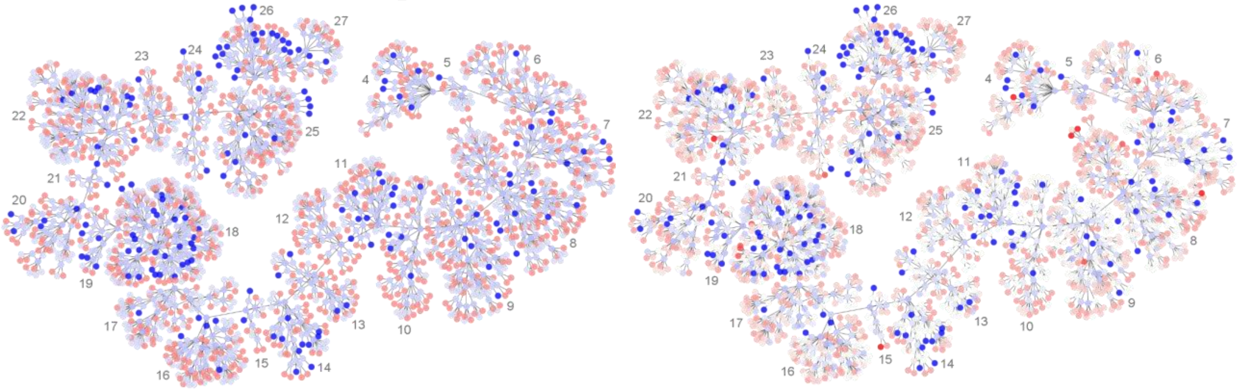
b) complete network

Figure 4.16 Clustering coefficient distributions for ACI 318-11 and ACI 318-14 implicit (a) and complete (b) networks.



(a) ACI 318-11 implicit

(b) ACI 318-11 complete



(c) ACI 318-14 implicit

(d) ACI 318-14 complete

standard deviations from mean: -2≤ -1 0 1 ≥2

Figure 4.17 ACI 318 clustering scoresfor implicit and complete networks.

While the clustering coefficient indicates the prevalence of connected 3-node subgraphs in the network, motifs are used to identify *overexpressed* connection patterns in subgraphs of 3 or more nodes. Under-expressed subgraphs, compared to random, are identified as well but are not considered motifs. Figure 4.18 shows all non-isomorphic three-node subgraphs and their corresponding identification (ID). For three nodes, 13 non-isomorphic variations exist. Adding a fourth node increases the variations to 199 while 5 and 6 node subgraphs have 9364 and 1,530,843 variations, respectively (Harary and Palmer 1973). The frequency of individual subgraphs in a real network are determined to have statistical significance by comparing them to the subgraph frequencies found in a number of random synthetic networks created using the configuration model[†], which preserves the real network’s joint degree sequence[†] (Milo et al. 2002). That is, the synthetic networks preserve nodal in and out-degrees and reconnect the nodes randomly via edge switching.

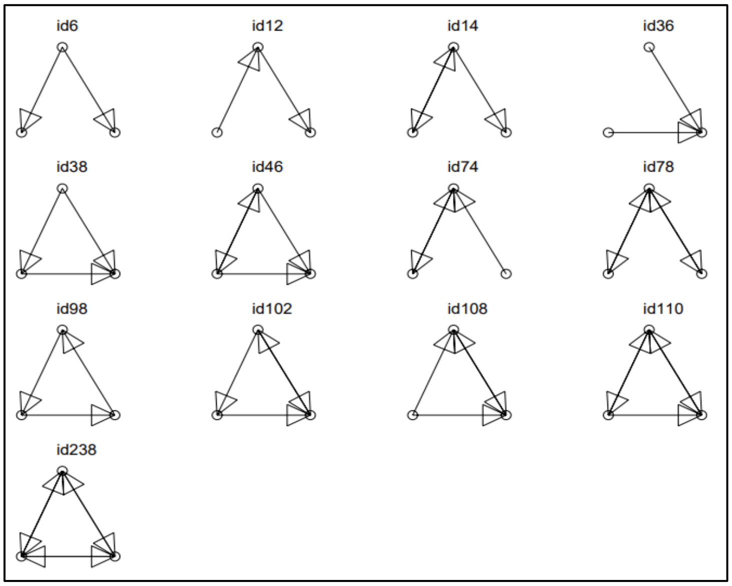


Figure 4.18 Nonisomorphic 3-node subgraphs in a connected directed network, adapted from Kashtan et al. (2005). ID38 is fundamental to the network definition adopted here, while IDs 98, 102, 110, and 238 all represent cyclic referencing.

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[13] (Kashtan et al. 2005). Statistics are based on 1000 synthetic networks generated using a configuration model parameterized by the real network. Motif criteria included a z-score greater than 2, with p-value less than 0.010, and at least 4 occurrences not sharing nodes (uniqueness). Motif IDs from mFinder are derived from the subgraphs' adjacency matrix using a binary translation. To illustrate, consider ID 38, the 3-node 'feedforward-loop' shown in Figure 4.18, which is the most common motif across both ACI 318 networks, by far. The subgraph ID 38 can be represented by the 3x3 adjacency matrix:

$$\begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \end{bmatrix}$$

written as binary with the least significant bit on the left, we obtain the motif ID:

$$(000100110)_{2} = 38 \text{ .}$$

A summary of results of the mFinder analysis is presented in Table 4.12 and a detailed report for subgraphs of size 3 is presented in Table 4.13. Statistics for larger subgraphs can be found in the supporting documentation. 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 less discriminately in ACI 318-11. Without a rigorous investigation, it is not clear how those motifs function within the standard and how they may affect the user experience. A hypothesis is that identifying and eliminating unnecessary motifs will likely improve the

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[13] Version 1.2

consistency of the standard and in turn the user experience. Separating necessary from unnecessary or functional from dysfunctional is not likely to be a straightforward task, but marginal motifs may be a proper place to begin an investigation for dysfunction.

Table 4.12 Motifs found across ACI 318-11 and ACI 318-14

		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	78, 92, 344, 394, 472	40 motifs
	5	24 motifs	462 motifs	24 motifs	307 motifs
Criteria: z-score > 2, p-value<0.010, uniqueness >= 4					

Table 4.13: ACI 318-11 and ACI 318-14 3-node subgraphs

	ID	Real Freq.	Synthetic Mean ± STD	z-score	p-value	Concentration (x 10^-3)
ACI 318-11 Implicit	6	4703	6098.4 ± 2.4	-574.31	1.000	452.23
	12	4288	5681.0 ± 4.7	-296.86	1.000	412.37
	14	0	0.0 ± 0.0		1.000	0.00
	36	0	1399.3 ± 2.4	-576.33	1.000	0.00
	38	1406	5.7 ± 2.4	576.80	0.000	135.21
	46	0	0.0 ± 0.0		1.000	0.00
	74	0	0.0 ± 0.0		1.000	0.00
	78	0	0.0 ± 0.0		1.000	0.00
	98	0	1.8 ± 1.3	-1.35	1.000	0.00
	102	0	0.0 ± 0.0		1.000	0.00
	108	0	0.0 ± 0.0		1.000	0.00
	110	0	0.0 ± 0.0		1.000	0.00
ACI 318-11 Complete	6	6046	7851.4 ± 4.4	-411.96	1.000	308.77
	12	8627	10507.5 ± 8.3	-227.76	1.000	440.61
	14	371	504.8 ± 1.3	-105.73	1.000	18.95
	36	2285	4031.1 ± 4.4	-399.68	1.000	116.70
	38	1728	18.6 ± 4.3	394.39	0.000	88.26
	46	38	0.3 ± 0.5	74.57	0.000	1.94
	74	263	524.4 ± 1.6	-158.97	1.000	13.43
	78	9	21.9 ± 0.2	-52.83	1.000	0.46
	98	48	5.4 ± 2.3	18.65	0.000	2.45
	102	46	0.6 ± 0.8	58.07	0.000	2.35
	108	102	0.5 ± 0.7	143.39	0.000	5.21
	110	13	0.1 ± 0.2	57.14	0.000	0.66
	238	0	0.0 ± 0.0	-0.03	1.000	0.00
ACI 318-14 Implicit	6	4459	6052.8 ± 2.1	-759.53	1.000	396.88
	12	5115	6703.6 ± 4.4	-364.81	1.000	455.27
	14	0	0.0 ± 0.0		1.000	0.00
	36	0	1593.7 ± 2.0	-780.93	1.000	0.00
	38	1598	4.3 ± 2.0	783.50	0.000	142.23
	46	0	0.0 ± 0.0		1.000	0.00
	74	0	0.0 ± 0.0		1.000	0.00
	78	0	0.0 ± 0.0		1.000	0.00
	98	0	1.7 ± 1.3	-1.32	1.000	0.00
	102	0	0.0 ± 0.0		1.000	0.00
	108	0	0.0 ± 0.0		1.000	0.00
	110	0	0.0 ± 0.0		1.000	0.00
ACI 318-14 Complete	6	5316	7276.2 ± 3.8	-515.11	1.000	263.42
	12	9867	11875.5 ± 7.5	-267.19	1.000	488.93
	14	145	181.8 ± 0.6	-64.26	1.000	7.18
	36	2638	4527.2 ± 3.8	-499.28	1.000	130.72
	38	1896	13.8 ± 3.8	497.20	0.000	93.95
	46	7	0.0 ± 0.2	33.12	0.000	0.35
	74	84	262.6 ± 0.8	-225.36	1.000	4.16
	78	3	8.0 ± 0.1	-74.53	1.000	0.15
	98	41	4.9 ± 2.2	16.37	0.000	2.03
	102	18	0.1 ± 0.4	45.75	0.000	0.89
	108	78	0.1 ± 0.3	225.53	0.000	3.87
	110	5	0.0 ± 0.1	79.11	0.000	0.25
	238	0	0.0 ± 0.0		1.000	0.00

Shaded rows indicate motifs not identified in each network.

Motifs are structures statistically important to the network and can be studied to identify their functions. For instance, cyclic subgraph structures (e.g., IDs: 46, 98, 102, 110, 238 for 3-node subgraphs in Figure 4.18) in a standard can 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. However, end-users report that circular referencing is challenging to manage, and investigators identify these as areas of conflict within a standard (Fenves 1987). The concentration of cyclic subgraphs of size 3 decreased from ACI 318-11 to ACI 318-14. Though they did not meet the motif criteria in either network, ID's 98, 102, and 110 represent forms of circular referencing and respectively occur in concentrations 1.2, 2.6, and 2.6 times greater in ACI 318-11 than in ACI 318-14 (Figure 4.19). Figure 4.19 shows that both standards share similar expression patterns. 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 synthetic models, concentrations do not always track) than their ACI 318-11 counterparts in almost all cases.

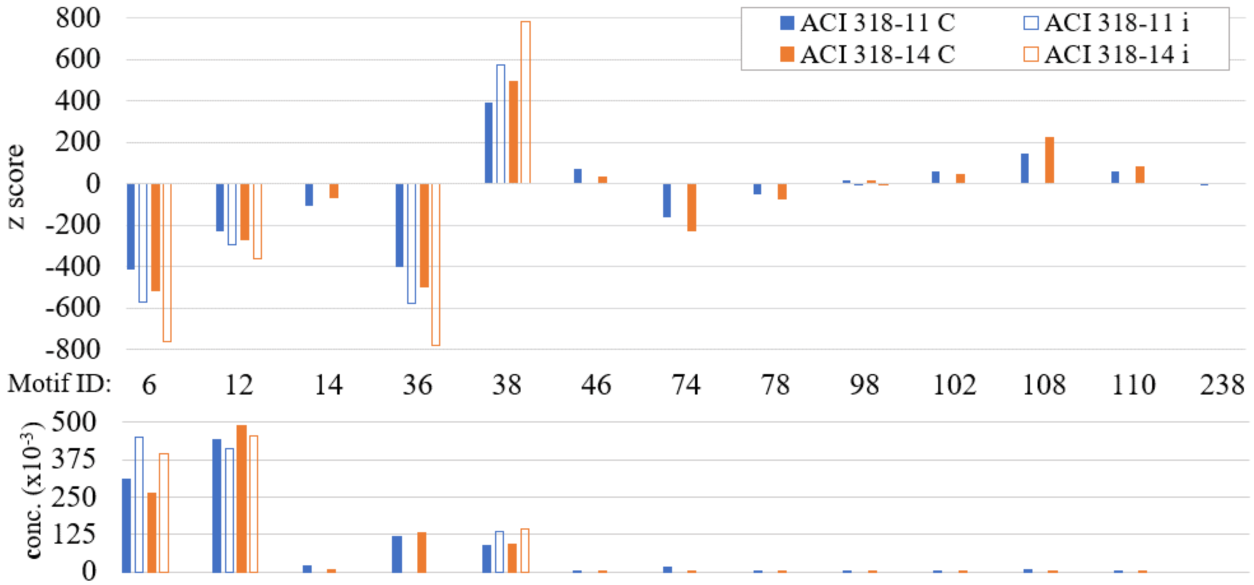

Figure 4.19 ACI 318 motif z-scores and concentrations implicit and complete networks. Z-score indicates the magnitude of deviation from the subgraph concentration found real networks compared to the synthetic networks (n=1000). Subgraph concentration is indicated by the scatterplot, lines between points are only for easy reading.

4.2.4 Grouping Nodes by Connectivity

Large clusters of nodes can be identified based on their connectivity to each other using the Girvan-Newman algorithm[14]. Heuristically, clustering aims to maximize inter-group edges and minimize intra-group edges. The Girvan-Newman algorithm successively removes important edges from the original graph until the modularity score (Eq. 4.8) is maximized (Newman, 2010). Edge importance was measured by edge betweenness centrality scores, which are calculated using Equation 4.9 for the edges in each sub-network for each loop of the algorithm.

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[14] implemented in NetworkX version 3.0

$$Q_c = \frac{1}{2m} \sum_{i \neq j} \left(A_{ij} - \frac{k_i k_j}{2m} \right) \delta_{ij} \tag{4.8}$$

is the modularity score of a partition of the network, where:
A is the adjacency matrix of the network,
k_i is the total-degree of node i,
m is the number of edges and,
δ_{ij} is the Kronecker delta function.

$$C_b(e) = \sum_{st} \frac{n_{st}^e}{g_{st}} \tag{4.9}$$

is the edge betweenness centrality 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
$n^e_{st}/ g_{st} = 0$ by convention if $g_{st} = 0$.

Newman and Girvan’s 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 (Newman 2016). Modularity score maximization assumes communities within a network are statistically similar (assortative), which may not be true of reference networks derived from standards, where chapters or sections serve a variety of roles. The modularity score was maximized at 33 partitions for both ACI 318-11 and ACI 318-14. Nodes within each partition are placed in rings in Figure 4.20 and Figure 4.21, representing clusters found within ACI 318-11 and ACI 318-14, respectively. Many chapters from each network tend to cluster together, though some more strongly than others. One shortcoming of this clustering approach is that it generates clusters of roughly 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.

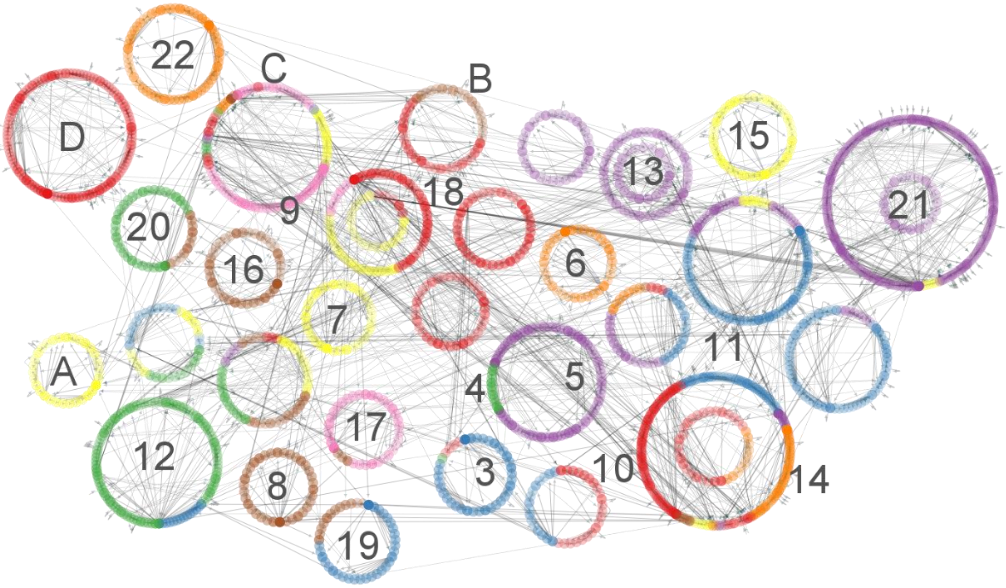


Figure 4.20 ACI 318-11 clustered by structure. Clusters were found using the Girvan-Newman algorithm with edge betweenness as the decision feature. The Girvan-Newman modularity score is maximized at 33 clusters, each indicated by a ring of nodes. Colors in this plot match those representing chapters from Figure 4.3. Chapter labels are located near the majority of the nodes from each chapter. Clusters are arranged so that clusters sharing provisions from the same chapter are near to each other; no other relationship is implied by this arrangement.

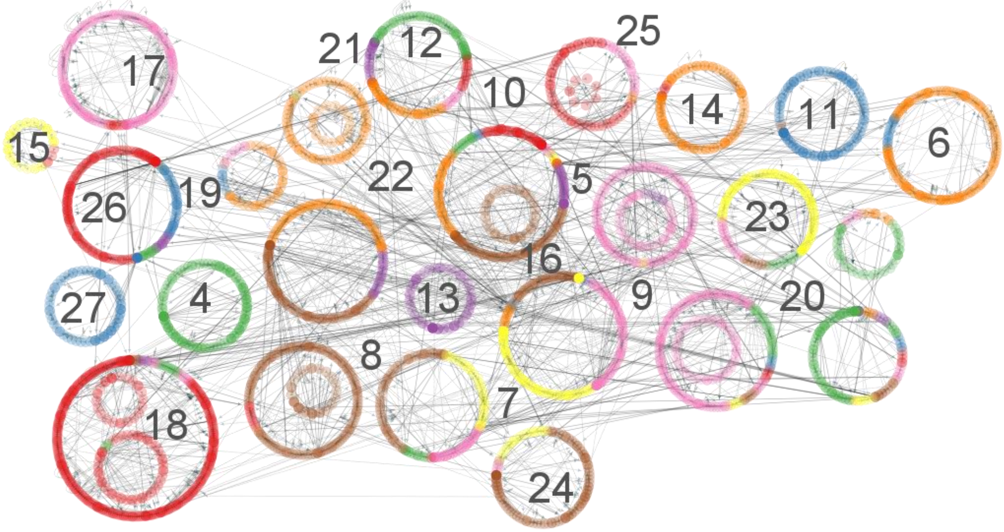


Figure 4.21 ACI 318-14 clustered by structure. Clusters were found using the Girvan-Newman algorithm with edge betweenness as the decision feature. The Girvan-Newman modularity score is maximized at 33 clusters, each indicated by a ring of nodes. Colors in this plot match those representing chapters from Figure 4.4. Chapter labels are located near the majority of the nodes from each chapter. Clusters are arranged so that clusters sharing provisions from the same chapter are near to each other; no other relationship is implied by this arrangement.

Cramer's V statistic (Eq. 4.10) can be used to measure association between nominal variables and is comparable across datasets with different scales (numbers of independent variables) (Liebetrau 1983).

$$V = \sqrt{\frac{\chi^2/n}{\min\,(c-1, r-1)}} \tag{4.10}$$

is Cramer's V, where:

if discrete variables A (i = 1, ..., r) and B (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:

$$\chi^2 = \sum_{i,j} \frac{(n_{ij} - \frac{n_{i.}n_{.j}}{n})^2}{\frac{n_{i.}n_{.j}}{n}} \tag{4.11}$$

where:

n_{ij} is the number of observations at (A_i, B_j),

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

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

Ranging from 0 to 1, Cramer's V indicates whether categorical frequencies are independent or perfectly associated, respectively. For the clusters identified using the Girvan-Newman algorithm, Cramer's V 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 slightly surprising, but likely due to the toolbox chapters which create links to many of the chapters.

4.2.5 Geodesic Paths

The geodesic (shortest) paths between all pairs of provisions in each of the explicit and implicit reference networks, as well as the complete networks, were found using the Floyd-Warshall algorithm (Floyd 1962). The geodesic paths are visualized in this work using heatmap representations. In these heatmap matrices, each geodesic path between two nodes is represented by a pixel where the vertical and horizontal ‘axes’ represent outgoing and incoming paths, respectively, by provision. Thus the vertical axis datum is the ‘source’ and the horizontal axis datum is the ‘target of a path. Because the network is directed, the plots are not symmetric about the diagonal. Recall that chapters 1 and 2 were excluded and lettered chapters are ACI 318 Appendices.

In the next Sections the heatmaps are presented in pairs (ACI 318-11 and ACI 318-14) based on the network type (implicit, explicit, and complete). These are followed by a plot showing the distribution of geodesic path lengths in the complete networks.

4.2.5.1 Implicit Networks

The implicit reference networks (heatmaps in Figure 4.22 and Figure 4.23) connect in the ‘forward’ direction, populating only the portion of the matrix above the main diagonal. The triangular ‘skylines’ to the right of the main diagonal indicate the relative number of provisions in each chapter and subchapters, since each subchapter will not implicitly reference out of the chapter.

For example, Chapter 4 will reference Chapter 5 but the last provision in Chapter 4 will not implicitly reference Chapter 5, creating an unclosed triangle along the diagonal in Figure 4.22 and Figure 4.23 . Likewise, by our network definition (Section 4.1), the last provision in a subchapter does not implicitly reference the next subchapter and therefore the subchapter is represented by a smaller, unclosed triangle along the diagonal within its chapter.

By inspection, ACI 318-11's chapter triangles (e.g., 8, 10, 12,18) appear slightly more dense than those of ACI 318-14, possible reflecting the trends seen in the implicit clustering distribution (Figure 4.17).

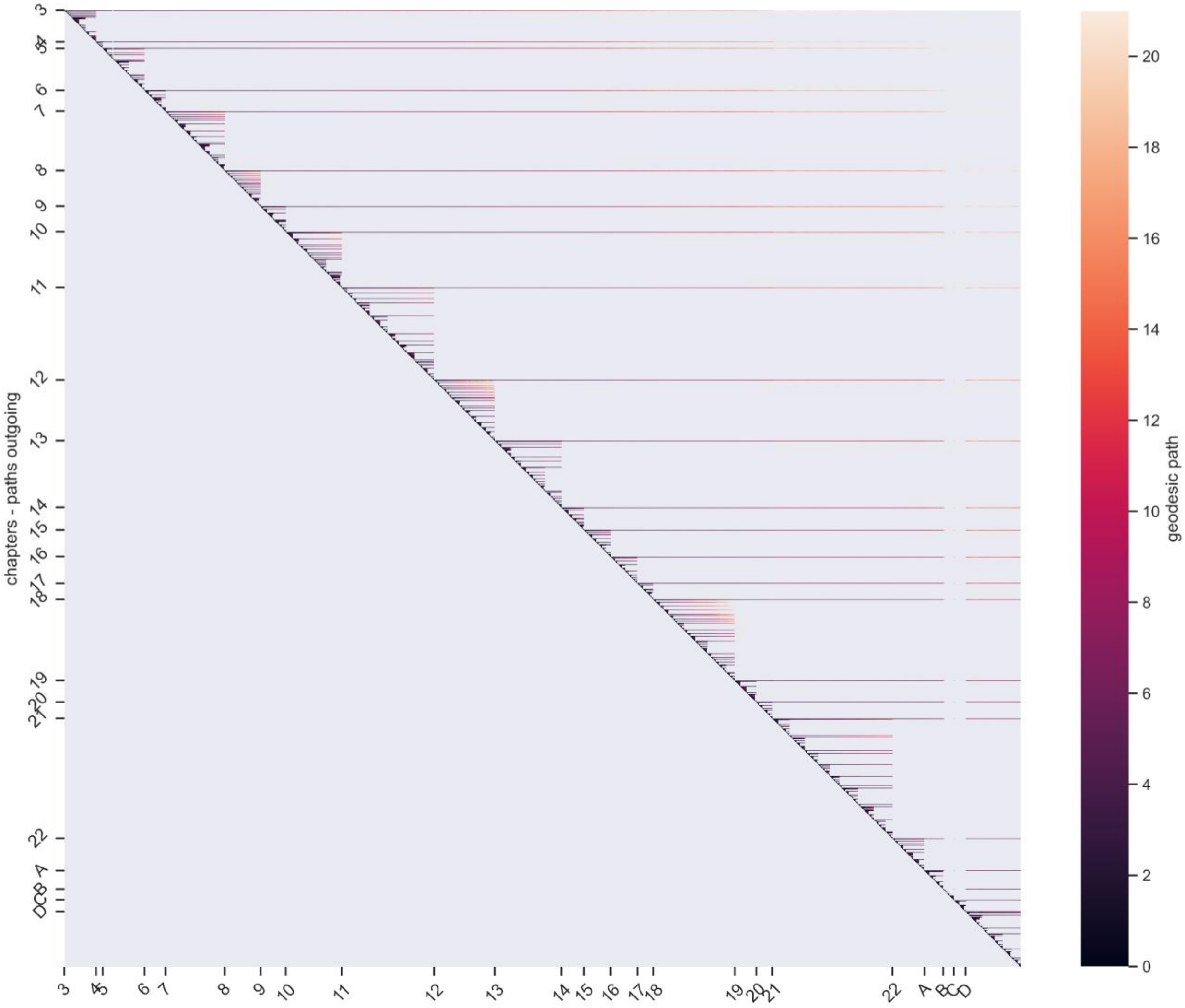


Figure 4.22 ACI 318-11 implicit network all-pairs geodesic paths. The break in Appendix B (right side of plot) is due to a break in the natural numbering of that chapter.

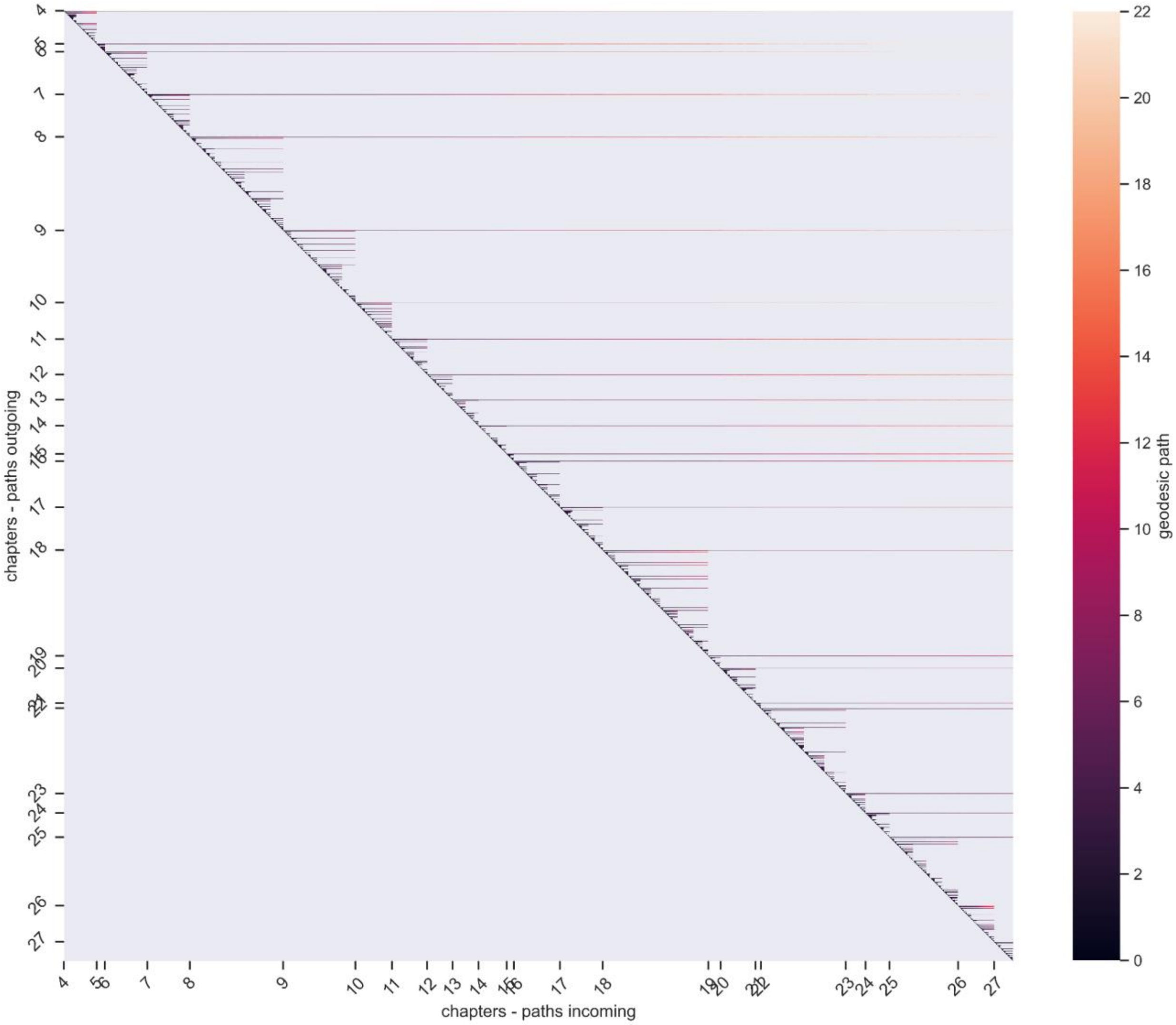


Figure 4.23 ACI 318-14 implicit network geodesic paths.

4.2.5.2 Explicit Networks

The explicit reference networks (heatmaps in Figure 4.24 and Figure 4.25) reach both forward and backward, but are sparse. As one would expect, paths are much shorter in the explicit networks than their implicit counterparts, because the explicit network is not connected. 59% of nodes in ACI 318-11 are active in the explicit network, compared to only 51% in ACI 318-14. By inspection, ACI 318-11 has more activity in the lower triangle than its own upper triangle and the lower triangle of ACI 318-14. The slight heat in the lower triangle of Figure 4.24 indicates references to previous chapters, which is believed to be disruptive to the ‘natural forward flow’ of the standard. These trends are also identified by the outgoing arrows in the chord diagrams of the each of the standards’ reference networks (Figure 3.1 and Figure 3.2).

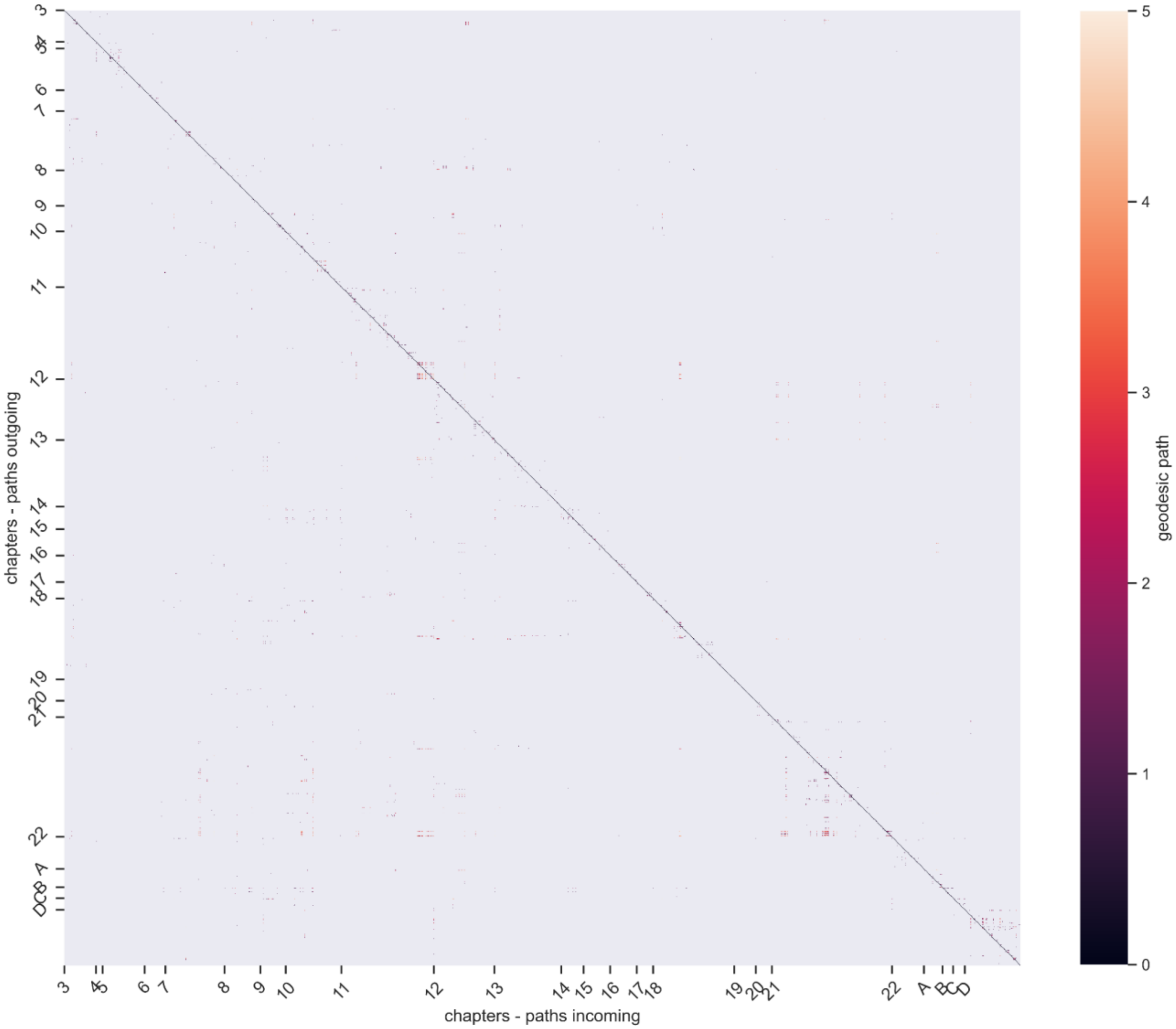


Figure 4.24 ACI 318-11 explicit reference network all-pairs geodesic paths.

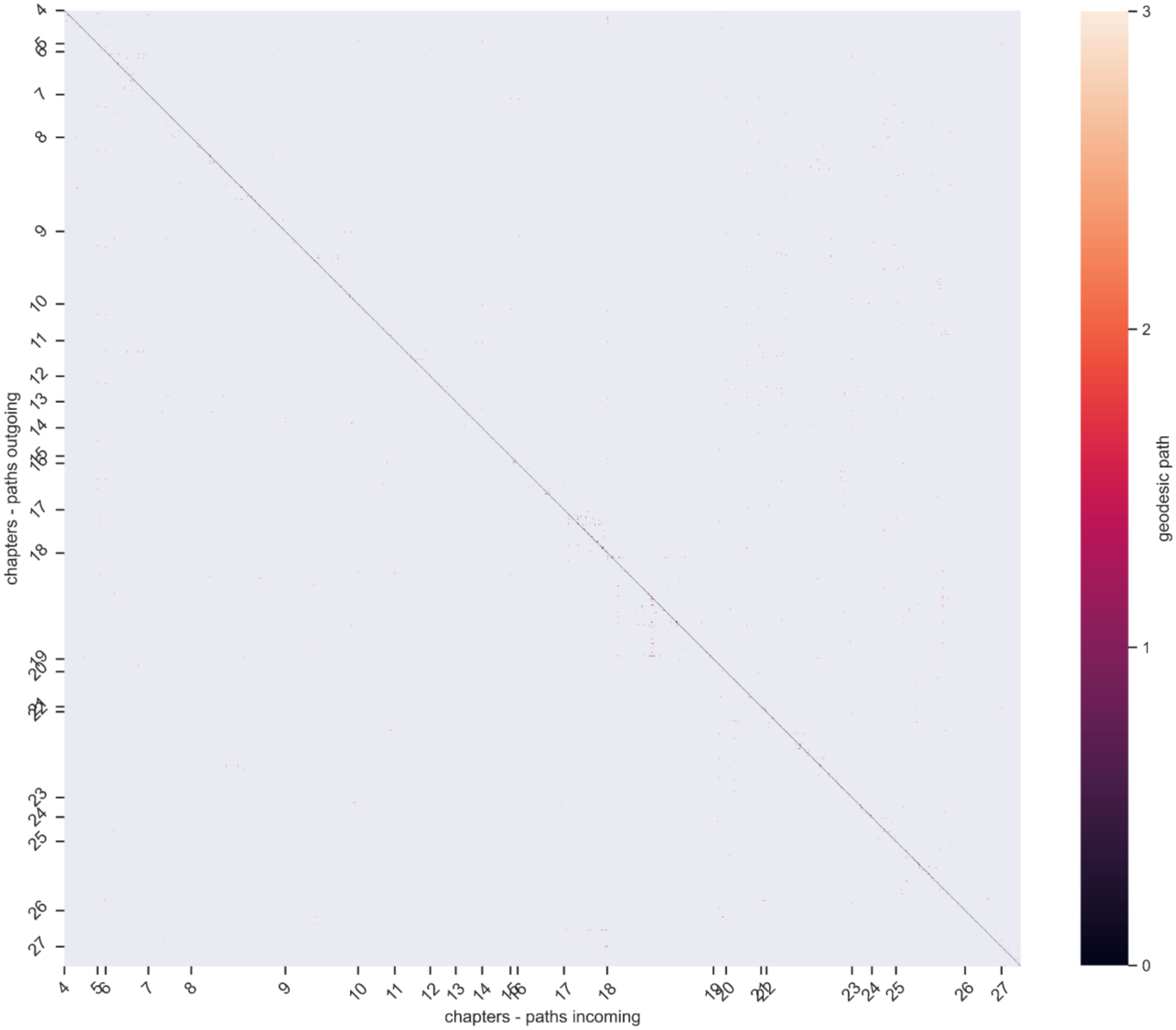


Figure 4.25 ACI 318-14 explicit reference network all-pairs geodesic paths.

4.2.5.3 Complete Networks

The complete reference networks (heatmaps in Figure 4.26 and Figure 4.27) exhibit traits from their constituent networks, but also emergent properties. By inspection, moving vertically through the complete network heatmaps, ACI 318-14 (Figure 4.27) appears less homogeneous than ACI 318-11 (Figure 4.26), a possible indication of specialized chapters and a modular hierarchy. For instance, grey horizontal 'bands' in these figures, broken only near the main diagonal (e.g., last half of chapter 10 in Figure 4.26, and more frequently in Figure 4.27) 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 the grey banding would be discontinuous. To demonstrate, if we examine paths out of Chapter 6 in Figure 4.27b, we see a short path to a specific clause in Chapter 19. 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 shortly reach Chapter 19. 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:

> ***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.* (ACI 318-14)

Now inspecting the heatmaps horizontally, ACI 318-11 relies heavily on references to previous provisions in the document (as seen by the darker regions ['heat'] below the main diagonal in Figure 4.26), a notable exception being “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 forward in the standard. ACI 318-14 appears to reference forward more heavily, particularly to the material and “toolbox” Chapters 19-25 (this is expected), with Chapters 5 “Loads” and 6 “Structural Analysis” being exceptions (but also chapters with exceptional topics). With the exception of Chapter 16, the typical references to Chapters 5 and 6 occur in subsection 4 “Required Strength” of each source “member” chapter, for example:

> ***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****. ...* (ACI 318-14)

One could debate the need for these provisions, particularly from the stance of minimizing the number of provisions, since in most cases they are not providing exceptions to the general rule of utilizing Chapters 5 and 6 for load and analysis, respectively. However, they 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 as they follow the typical design process, which may be the closest mental map end-users have of the standard. These references may also serve some other important function such as severability[†]. The arrangement of knowledge within the standard requires a balance of many objectives. Meeting the end-users’ expectations by matching their mental map, maintaining a consistent structure, and creating a rigorous/modular hierarchy appears to result in a better experience as reported by respondents to the survey presented in Chapter 3.

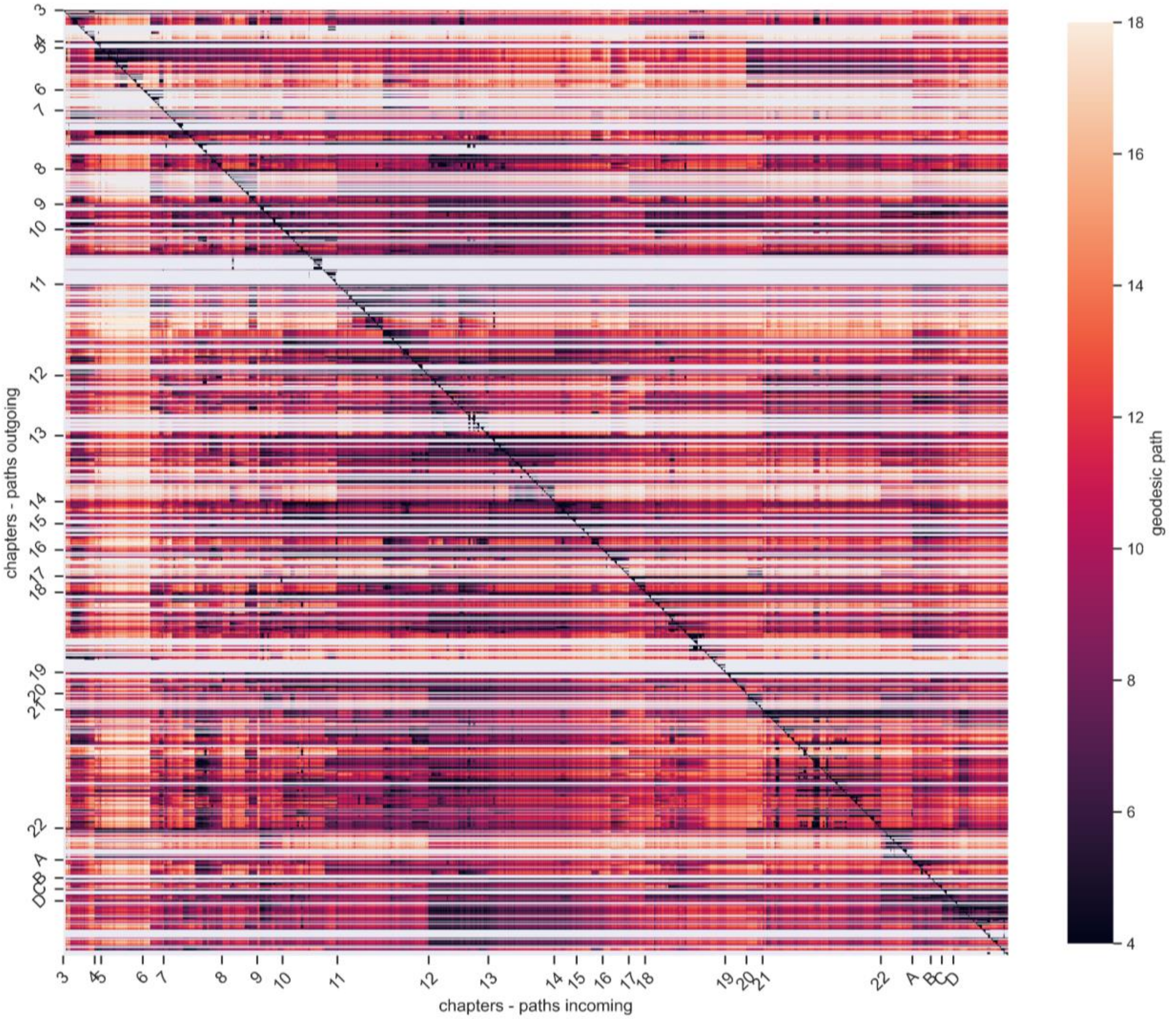
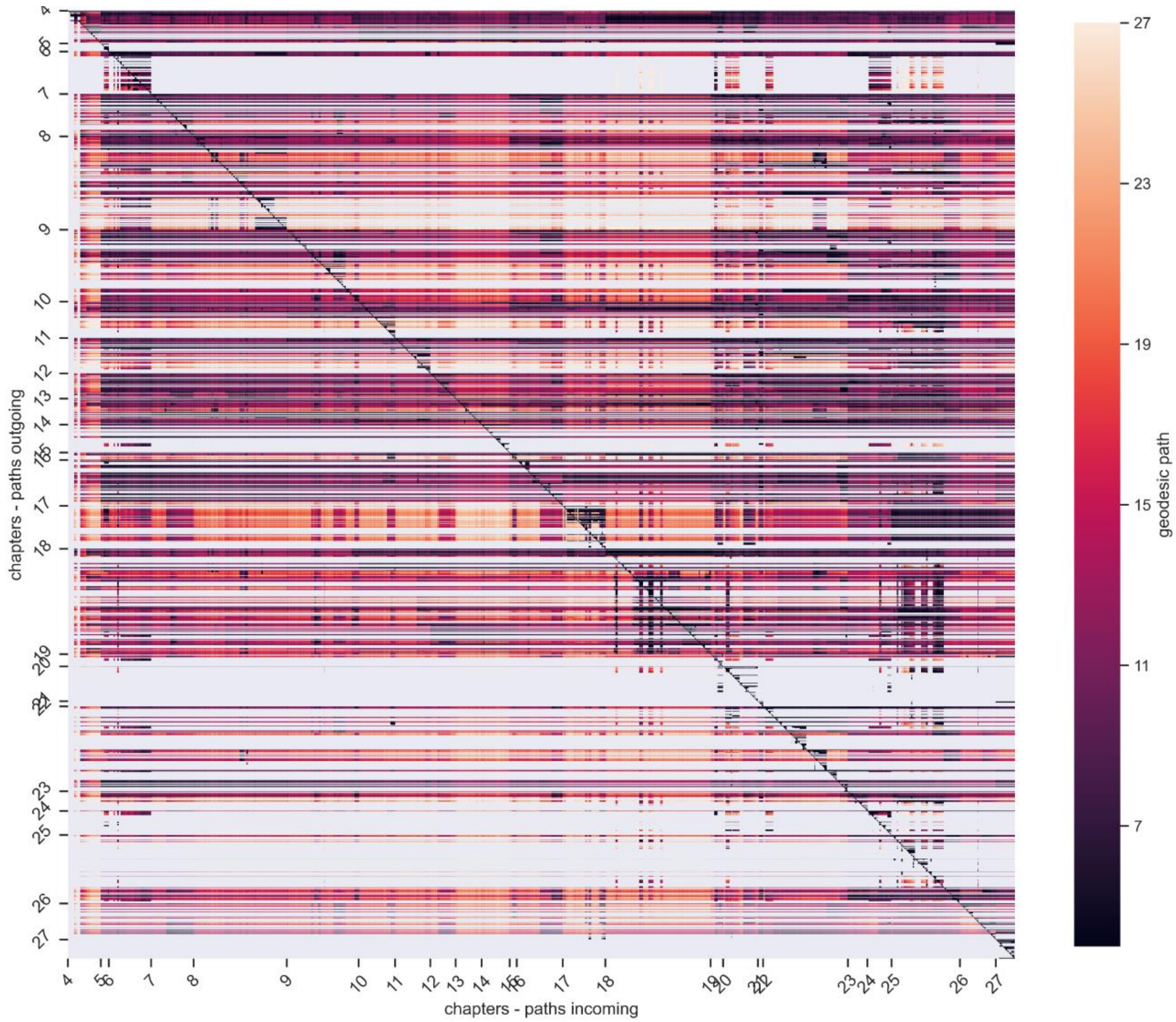
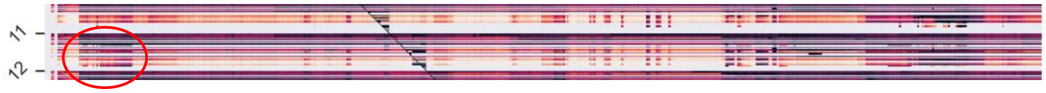


Figure 4.26 ACI 318-11 complete reference network all-pairs geodesic path lengths The prevalance of darker areas in the lower triangle indicate heavy ‘backwards’ referencing through the standard, particularly between Chapters 9-14. Grey horizontal bands, broken only near the diagonal (last half of chapter 10) indicate that the provisons are only reachable along the implicit path.



(a) Complete reference network Material and toolbox chapters (19-25) can be reached by many provisions quickly. Chapters 5 and 6 are a ‘Loads’ and ‘Structural Analysis’, special topics that are backreferenced by many provisions, potentially unnecessarily. Heat in the lower triangle of Chapter 18 may mean this chapter is due to be reorganized.

(b) short direct path from early Chapter 6 to Chapter 19 described in text (cropped from a).



(c) references from Chapter 11.4 to Chapters 5 and 6 described in text. (cropped from a).

Figure 4.27 ACI 318-14 complete reference network all-pairs geodesic path lengths.

4.2.5.3.1 Geodesic Paths Distributions

Distributions for the geodesic path lengths for all provisions in the complete reference networks are shown in Figure 4.28 and Figure 4.29 for ACI 318-11 and ACI 318-14, respectively. The cumulative curves were tested for best fit against common distributions and found to be well represented by a normal distribution in both cases. The distributions for both ACI 318-11 (skewness = 0.44) and ACI 318-14 (skewness = 0.65) demonstrate a positive skew.

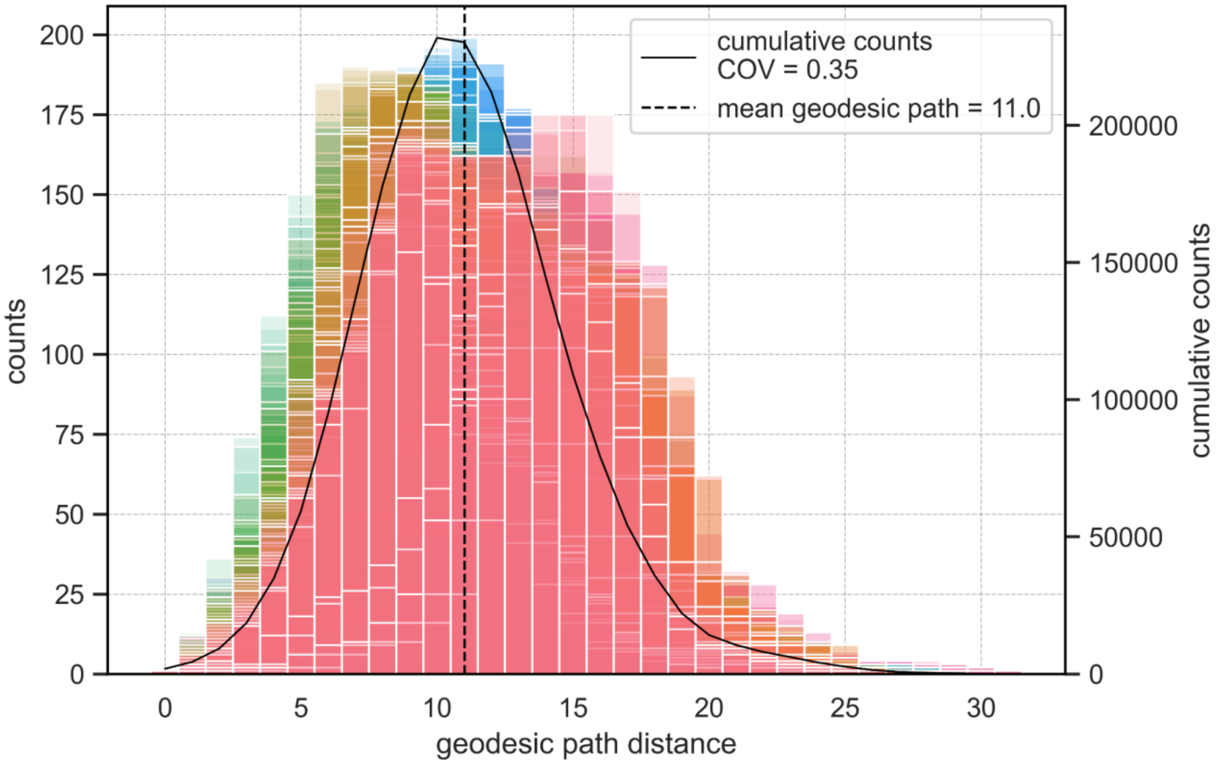


Figure 4.28 ACI 318-11 geodesic path length distribution. Colored by provision. The essentially normal cumulative distribution is indicated by the black line (kurtosis = 3.72, skewness = 0.44).

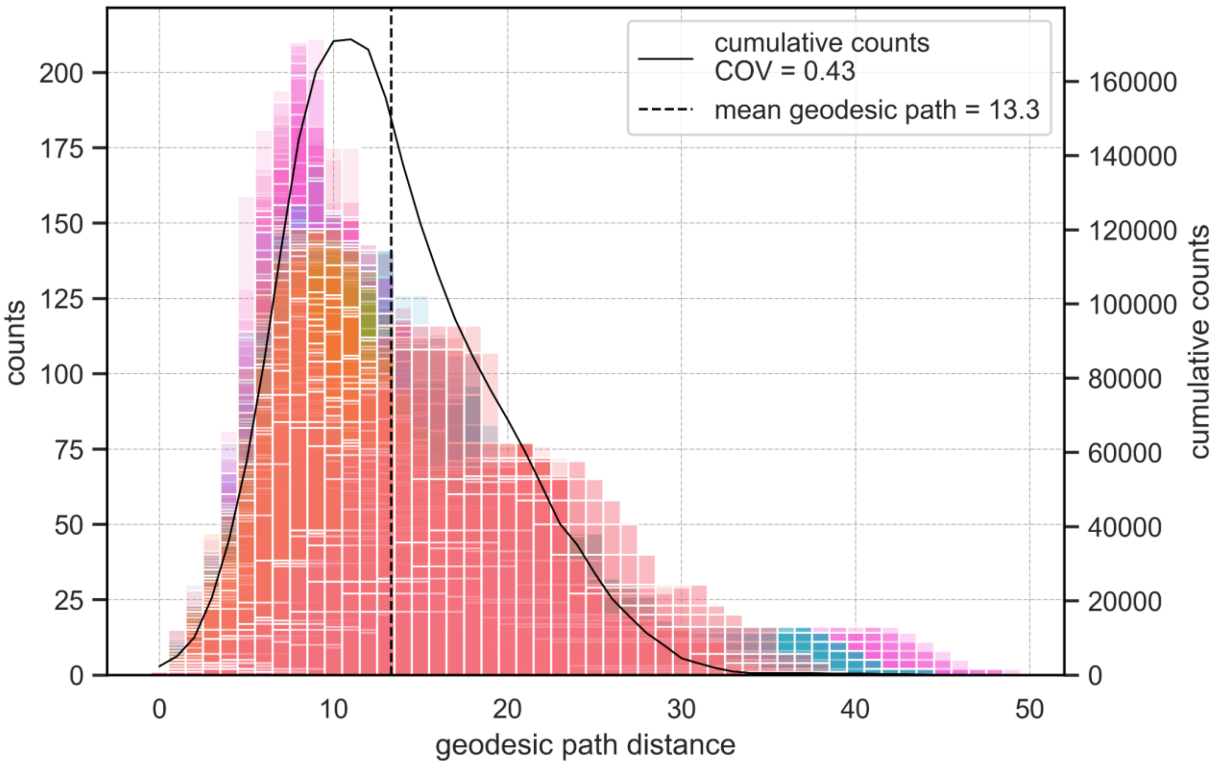


Figure 4.29 ACI 318-14 geodesic path lenghts distribution. Colored by provision. The essentially normal cumulative distribution is indicated by the black line (kurtosis = 3.42, skewness = 0.65).

4.3 Semantic Representation of Provisions

The stated goal of the ACI 318 revision was to reorganize the standard to match the design process more closely (Dolan and Feldman 2009), effectively organizing the standard to match an end-user's mental map of the design space. This serves to reduce navigational complexity by reducing uncertainty for the user. Stakeholders will not all share the same mental map of the design space based on their experience or expertise, while some may prefer a map more closely aligned to compliance checks of designs rather than the design space generally. SWB's are diverse but are not likely to be completely representative of the end-user demographic (indeed, they will usually be populated by highly experienced individuals). SWB's are not likely to seek end-user opinion on perceived complexity during a revision and are much less likely to receive feedback writing a standard within a non-conventional or marginal industry, such as for bamboo or rammed earth. Digital standards may allow for unique presentations of a standard to stakeholders. Hypothetically, the ideal presentation would match the end-user's mental map of a particular problem instance and include those things that the user may be unaware of. Such a presentation would require a deep semantic understanding of the content of the standard (and the end-user), traditionally associated with experienced engineers who develop guides or workflows.

NLP techniques are nascent but developing rapidly with current language models (tuned to chat applications) presenting human-like understanding over broad topics. As described in Section 2.6, these language models operate by encoding patterns in vast amounts of text data into a matrix space. Roughly, patterns that co-occur in the text space will be in close proximity in the matrix space. Models can be fine-tuned [trained] on niche topics for a variety of downstream tasks such as chatting, translating, classification, question-answering, or summarization. Moreover, modern chat models' 'voice' can mimic levels of human literacy, tone, or emotion. If one asks it, ChatGPT can present a workflow (albeit imperfect) to design a concrete beam in accordance with ACI 318-19, including both formulaic and qualitative considerations. This was attempted as an exercise by the author; the result is shown in Figure 4.30. With only one input, the output clearly lays out what needs to be done, although the workflow itself is unlikely to be that followed by a skilled designer. The result reads more like a step-by-step exam problem. Nonetheless, given current trends, in the near future a fine-tuned GPT3 or next generation model will likely be able to present the knowledge within ACI 318 as a novice or intermediate user.

Outline the steps for designing a simply supported and tension-controlled reinforced concrete beam with rectangular cross-section in accordance with ACI 318-19. Include all formulas.

Designing a simply supported and tension-controlled reinforced concrete beam with rectangular cross-section in accordance with ACI 318-19 can be done by following these steps:

1. Determine the design load:
   - Determine the load on the beam using the appropriate loading codes and standards.
2. Determine the beam dimensions:
   - Choose the width and depth of the beam based on the space available for the beam.
   - Use the span and the desired depth-to-span ratio to determine the depth of the beam.
   - Check the depth against the deflection limits.
3. Determine the effective depth:
   - Determine the effective depth of the beam as the distance from the extreme compression fiber to the centroid of the tension steel.
4. Determine the reinforcement required:
   - Calculate the required steel area for the tension steel using the ACI 318-19 equation for tension-controlled sections:

```
As = (0.85 * f'c / fy) * b * d
```

   where As is the area of tension steel, f'c is the compressive strength of concrete, fy is the yield strength of steel, b is the width of the beam, and d is the effective depth of the beam.
   - Use the minimum steel area required for durability, which is usually 0.0018 times the gross area of concrete.
   - Choose an appropriate reinforcement pattern and calculate the required steel area for the compression steel.
5. Check the deflection:
   - Check the deflection of the beam using the appropriate limits for serviceability.
6. Check the shear:
   - Check the shear capacity of the beam using the appropriate equations in ACI 318-19.
7. Check the development length:
   - Check the development length of the reinforcement using the appropriate equations in ACI 318-19.
8. Check the spacing and cover:
   - Check the spacing and cover of the reinforcement to ensure that the concrete cover is adequate for durability and fire resistance.
9. Draw the reinforcement details:
   - Draw the reinforcement details, including the dimensions, steel area, spacing, cover, and development length.
10. Check for constructability:

- Check the reinforcement details for constructability, including the ability to place and compact the concrete around the reinforcement.

11. Check the overall stability of the beam:

- Check the overall stability of the beam against lateral torsional buckling, excessive deflection, and other potential failure modes.

12. Finalize the design:

- Finalize the design, including the dimensions, reinforcement details, and any additional details or specifications required for construction.

Figure 4.30 ChatGPT-generated workflow (queried 23 February 2023)

This research considers two semantic representations of the standards, representing last-generation and current-generation language models, respectively: (1) spaCy's "en_core_web_lg-3.4" model with static vectors of 300 dimensions and (2) OpenAI's Generative Pre-trained Transformer 3 (GPT3) "text-similarity-curie-001" model with transformer-generated context vectors of 2048 dimensions. Neither model was tuned to the civil engineering knowledge domain due to the lack of available corpora; in theory, both models will provide more accurate results if so tuned. In addition to being a larger model with state-of-the-art transformer architecture, GPT3 was also pre-trained for cosine similarity between texts with up to 2048 tokens and is therefore expected to produce results more representative of human understood similarity. Each model represents text input as a vector embedding, as described in Section 2.6.

Here, spatial relations between the provisions in the models' space and the reference network are explored. First, provisions are clustered by k-means using vector embeddings. These clusters are tested for association with the structural clusters identified in Section 4.2.4, as well those defined by the document chapters. Then, similarity between provision embeddings is mapped for all provision pairs, again utilizing both GPT3 and spaCy embeddings. Finally, the hypothesis that provisions sharing semantic similarity are physically closer in the revised standard is tested by finding the correlations between geodesic path length and similarity score for node pairs.

4.3.1 Clustering Provisions by Embedding

k-means[15] clustering was identified as a candidate clustering algorithm candidate based on the shape of the data observed in the Principal Component Analysis (PCA) reduction of the embedding space, in addition to the high-dimensionality and large number of degrees of freedom in the data. k-means partitions n observations into k clusters, where each observation is closer to the centroid of its cluster than to others, measured by the squared Euclidian distance. k-means clusters are influenced by the initial random state (centroid locations) of the algorithm; only a local optimum is guaranteed. k-means generates clusters with similar geometric size in the embedding space, which may not be representative of the expected clusters. Gaussian mixture analysis was not pursued here but could be used to identify clusters with varied sizes. The nearest neighbor approach may produce more consistent results for embeddings generated using GPT3, given the shape of the normalized space. There are trade-offs with any clustering algorithm, but k-means serves as a strong middle ground for this analysis.

The ideal number of clusters (which must be known ahead of analysis) can be determined by optimizing the silhouette score or by selecting the 'elbow' of the summed squared error plot. The silhouette coefficient for each data point is a measure of the distance from that node to the closest neighboring cluster, with +1 indicating far away (a good fit), 0 indicating the point is close to the decision boundary of two clusters, and -1 indicating the point may be in the incorrect cluster (Rousseeuw 1987). The 'appropriate' number of clusters can be identified by selecting the clustering instance which maximizes the average silhouette score for the network. A similar

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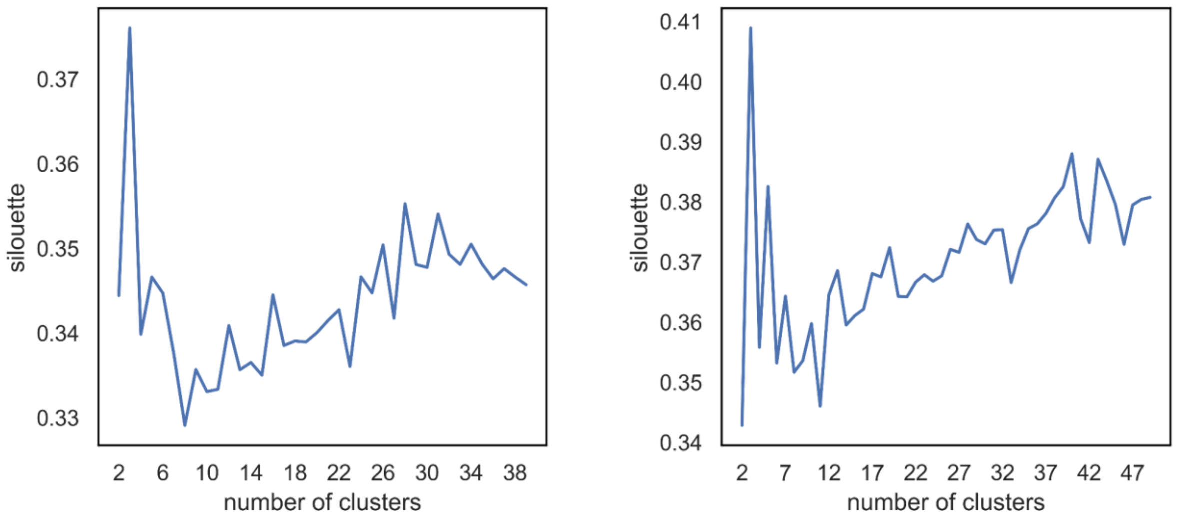
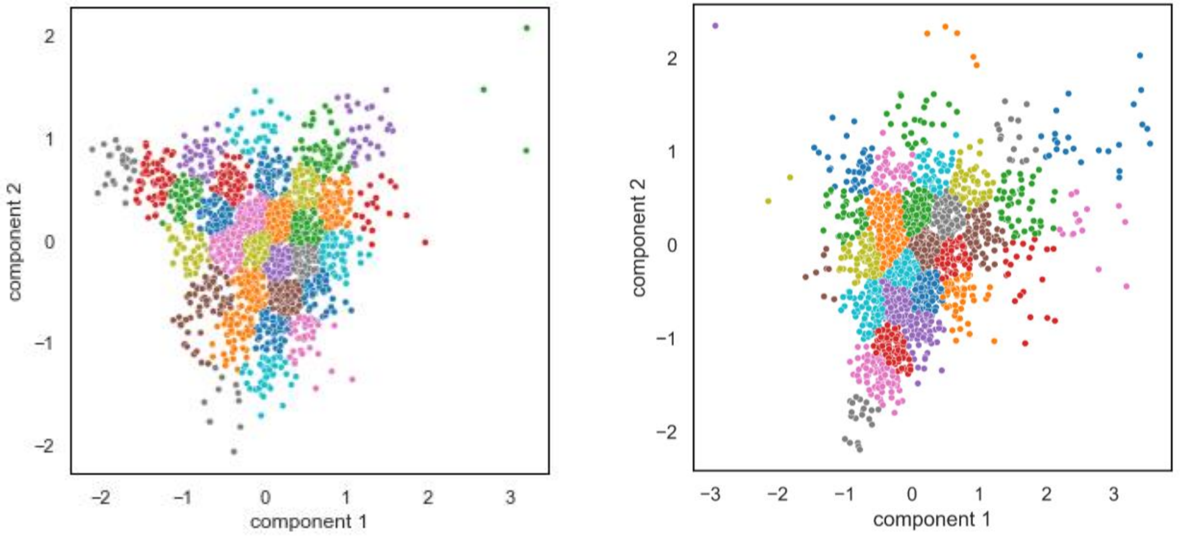
[15] Lloyd's implementation in scikitlearn v1.2.1

procedure can be followed, where finding the ‘elbow’ of the summed square error plot identifies an appropriate number of clusters. However, this method is sensitive to the number of clusters tried (plotted) so is not presented here. Ultimately, 33 clusters (identified by the structural clustering in Section 4.2.4) were used here for clustering the embeddings because silhouette analysis found a similar maximum. Having the same number of clusters also facilitates a comparison between the semantic and structural clusters (Figure 4.31 [a, b]). The clustered spaCy embedding space for ACI 318-11 and ACI 318-14 is visualized in Figure 4.31(c, d) using PCA to reduce data dimensionality. Similarly, silhouette analysis and clusters for ACI 318-11 and ACI 318-14 embeddings in the GPT3 embedding space is presented in Figure 4.32. The GPT3 embedding space is optimized for cosine similarity, which shapes the distributions in Figure 4.32 (c, d).

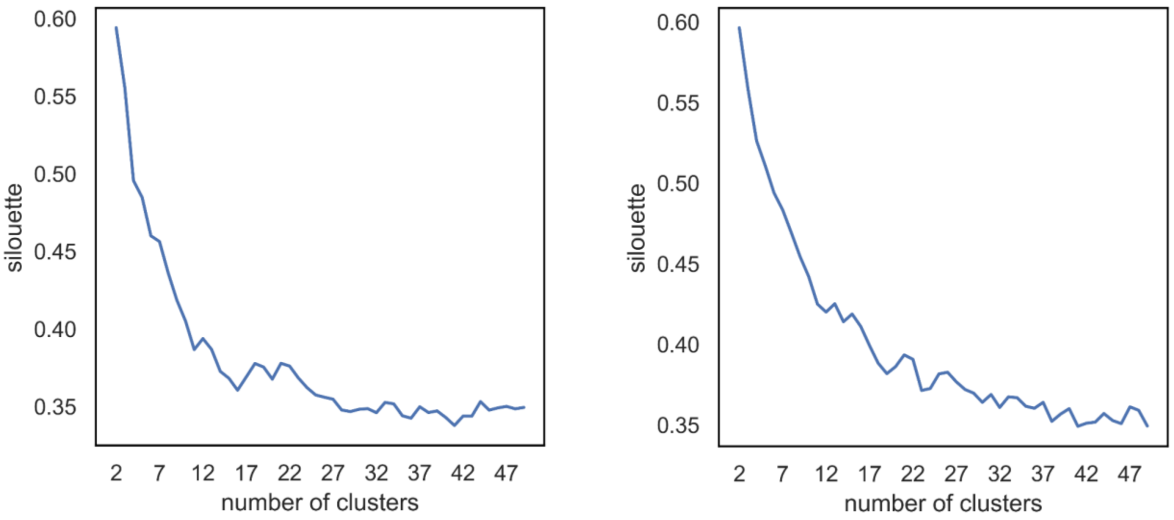


(a) ACI 318-11 **(b) ACI 318-14**

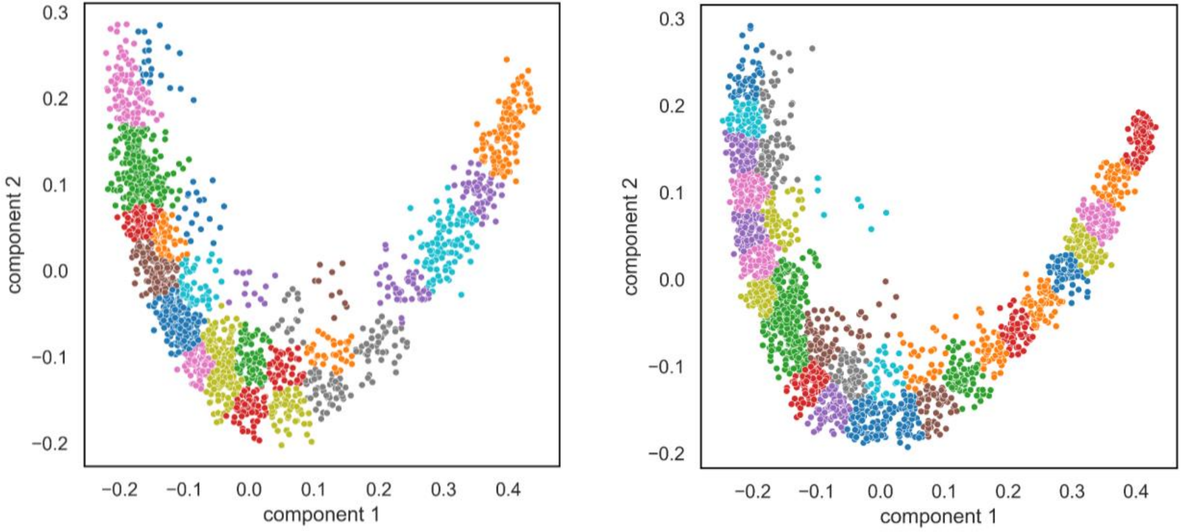


(c) ACI 318-11 **(d) ACI 318-14**

Figure 4.31 ACI 318 spaCy silhouette analysis (a, b) and clusters (c, d) visualized using PCA. Cluster colors are only for visualization, some neighboring clusters share colors.



(a) ACI 318-11 **(b) ACI 318-14**



(c) ACI 318-11 **(d) ACI 318-14**

Figure 4.32 ACI 318 GPT3 silhouette analysis (a, b) and clusters (c, d) visualized using PCA. Cluster colors are only for visualization, some neighboring clusters share colors.

For some measure of the meanings of the clusters, Table 4.14 presents the terms closest to the centroids of each cluster in the spaCy embedding space. Some of the terms near centroids one might expect to be represented by a chapter or section in ACI 318, although just as many would not. This is likely a limit imposed by the limited tokens in the embedding space, the lack of context for input vectors (see ‘moments ~ imagine’ in cluster 6 of ACI 318-14), and the vector averaging process (notice prevalence of ‘thus’, ‘necessary’, etc.). Table 4.15 presents a slightly different analysis for the GPT3 embedding space. Because the GPT3 API will not return tokens from an embedding input, the five provisions that are the nearest neighbors to each cluster centroid are shown. By inspection, many of the five nearest neighbors are from the same chapter or sections in the standard, although on average there are 61 provisions in each cluster (given approximately 2000 provisions and 33 clusters). Therefore, it is unclear from this analysis to what extent the chapters and clusters are associated. Statistical association between these groups is discussed in the next section.

Table 4.14: ACI 318-11 and ACI 318-14 spaCy embeddings cluster centroids. Unique terms from 10 nearest to k-means cluster centroids are shown each standard.

ID	ACI 318-11	ACI 318-14
0	{'apart', 'end', 'sides'}	{'necessary', 'thus', 'i.e.'}
1	{'thus', 'therefore', 'which'}	{'terms', 'certain', 'general'}
2	{'thus', 'necessary', 'sufficient'}	{'thickness', 'shear', 'tensile'}
3	{'thus', 'necessary', 'sufficient'}	{'member', 'connection', 'members'}
4	{'necessary', 'sufficient', 'strength'}	{'design', 'strength', 'flexibility'}
5	{'thus', 'necessary', 'therefore'}	{'accordance', 'shall', 'appropriate'}
6	{'(', '=', 'equal', 'i.e.', ')'}	{'moments', 'moment', 'imagine'}
7	{'beams', 'walls', 'wall'}	{'thus', 'sufficient', 'therefore'}
8	{'each', 'above', 'i.e.'}	{'structural', 'analysis', 'evaluation'}
9	{'construction', 'concrete', 'structural'}	{'reinforcing', 'reinforcement', 'longitudinal'}
10	{'rather', 'thus', 'hence'}	{'scopes', 'objective', 'scope'}
11	{'thus', 'surface', 'structure'}	{'thus', 'sufficient', 'necessary'}
12	{'tensile', 'shear', 'strength'}	{'wires', 'welded', 'wire'}
13	{'concrete', 'necessary', 'materials'}	{'broader', 'objective', 'scope'}
14	{'transverse', 'longitudinal', 'reinforcement'}	{'compressive', 'shear', 'tensile', 'shearing'}
15	{'accordance', 'necessary', 'shall'}	{'way', 'be', 'so'}
16	{'concerned', 'general', 'reasons'}	{'required', 'sufficient', 'necessary'}
17	{'scope', 'broader', 'objective'}	{'formwork', 'precast', 'pre-cast', 'footings'}
18	{'reinforcing', 'reinforced', 'reinforcement'}	{'material', 'recycled', 'materials'}
19	{'rather', 'necessary', 'be'}	{'(', 'i.e.', 'or', 'e.g.', ')'}
20	{'design', 'methods', 'approach'}	{'greater', 'limiting', 'limits'}
21	{'columns', 'column', 'rows'}	{'appropriate', 'required', 'necessary'}
22	{'footings', 'foundations', 'concrete'}	{'substantially', 'sufficient', 'necessary'}
23	{'steel', 'reinforced', 'welded'}	{'torsion', 'tensile', 'torsional', 'axle'}
24	{'thus', 'necessary', 'i.e.'}	{'reinforced', 'reinforcing', 'reinforcement'}
25	{'thus', 'sufficient', 'thereby'}	{'thus', 'each', 'i.e.'}
26	{'thus', 'cured', 'curing'}	{'concerned', 'reasons', 'general'}
27	{'pilings', 'footings', 'piers'}	{'material', 'property', 'properties'}
28	{'apart', 'thus', 'necessary'}	{'column', 'columns', 'rows'}
29	{'appropriate', 'necessary', 'required'}	{'reinforcing', 'prestressed', 'structural'}
30	{'necessary', 'determine', 'required'}	{'construction', 'concrete', 'structural'}
31	{'horizontal', 'substantially', 'perpendicular'}	{'applicable', 'accordance', 'shall'}
32	{'necessary', 'structure', 'concrete'}	{'shear', 'strength', 'tensile'}

Table 4.15: ACI 318-11 and ACI 318-14 GPT3 embeddings cluster centroids. 5 nearest neighbors to k-means cluster centroids are shown for each standard.

ID	ACI 318-11	ACI 318-14
0	12.18.1 , 12.19.1.2, 12.19.1.1 , 12.2.1 , 12.15.2	17.2.3.6, 17.2.3.5.4 , 17.2.3.4.2 , 17.2.3.4.5 , 17.5.1.1
1	21.1.1.2, 11.6.3.1 , 21.3.5.5 , 21.1.5.5 , 14.2.3	11.7.1, 11.8.1 , 11.4.1 , 11.5.1 , 12.7.1
2	6.3.3, 6.4.3 , 6.1.6 , 6.3.10 , 6.3.11	16.2.1.4, 16.3.2.1 , 16.2.4.1 , 16.2.1.8 , 16.4.2.1
3	3.6, 7.3 , 8.1 , 8.3 , 7.5	11.2.1, 11.6 , 10.7.2 , 10.7.6 , 10.7
4	5.6.3.3, 5.1.1 , 5.2.1 , 5.6.5.4 , 5.3.1.1	9.7.3, 8.7.4 , 9.6.2 , 8.7.5 , 9.6.1
5	10.2.1, 10.3.5 , 10.10.2.1 , 10.13.2 , 10.6.3	22.5.10.2, 22.4.2.5 , 22.6.1.8 , 22.6.1.5 , 22.5.8.3.4
6	16.5.1, 16.2.1 , 16.5.2.3 , 15.8.1.4 , 15.8.1.3	24.5.1.1, 22.4.2.5 , 24.4.4.1 , 25.9.4.4.2 , 25.9.5.1
7	11.1, 21.5.4 , 11.4 , 21.9.4 , 21.6.5	8.7.4.1.1, 8.3.2.1 , 8.7.5.5.1 , 8.4.1.2 , 8.7.4.1.3
8	12.15.4, 12.15.6 , 12.17.2.1 , 12.17.3 , 12.17.2.3	9.6, 9.5.2 , 9.9.3 , 9.7.2 , 9.2.1
9	18.11.2.2, 21.11.7.1 , 16.5.1.3 , 21.11.7.6 , 7.13.2.2	10.5.3.1, 11.5.1.2 , 10.5.1.2 , 9.5.3.1 , 11.5.5.1
10	10.13.6, 21.9 , 9.5.4 , 11.3 , D.5.2	8.10.5.6, 8.4.4.1.3 , 8.4.4.1.1 , 8.11.2.2 , 8.10.7.1
11	7.10.4, 10.6.2 , 10.7.3 , 10.13.7.2 , 8.13.5.3	9.7.4.2, 9.6.2.1 , 9.6.1.1 , 9.3.2.1 , 9.7.3.4
12	21.7.3.3, 21.3.5.1 , 21.5.2.1 , 21.5.1.4 , 21.11.7.6	26.4.1, 26.4.2 , 26.4 , 26.5.1 , 26.5.2
13	D.3.3.4.2, D.3.3.5.2 , D.6.2.8 , D.2.1 , D.7	11.7.1.2, 11.7.1.3 , 9.7.1.2 , 10.7.1.2 , 8.7.1.3
14	18.9.1, 18.3.1 , 18.10.1 , 18.13.3.2 , 18.9.4.1	4.12.1.1, 4.10.2.1 , 4.4.2 , 4.4.6.5.3 , 16.2.1.4
15	C.9.3.2.6, C.9.3.2.4 , 9.3.2.6 , 9.3.2.4 , A.5.2.1	10.7.3.2, 10.6.1.1 , 10.6.1.2 , 10.3.1.3 , 10.7.6.4.2
16	21.10.1, 21.8.1 , 21.4.1 , 21.1.4.1 , 21.1.5.1	18.7.5.1, 18.8.3.3 , 18.6.4.7 , 18.2.8.1 , 18.14.4.1
17	16.2, 16.1 , 18.1 , 18.2 , 14.1	26.4.2.2, 26.5.7.1 , 26.13.3.2 , 26.4.3.1 , 26.12.1.1
18	11.6.2, 11.9.2 , 11.11.3.4 , 11.4.3 , 11.11.5.4	6.6.4.3, 6.6.4.6.4 , 6.6.3.1.3 , 6.6.5.1 , 6.6.2.1
19	7.10.1, 7.11.1 , 7.10.2 , 7.12.3 , 7.11.2	22.4.3.1, 22.6.9.10 , 22.5.9.5 , 22.5.9.3 , 22.4.2.1
20	13.7.3.1, 13.7.4.1 , 13.6.8.4 , 13.6.1 , 13.5.1.1	18.1, 18.3.1 , 18.13.1 , 18.6.1 , 18.7.1
21	21.9.2, 21.5.2 , 21.6.3 , 22.1 , 21.7.3	8.7.5.6.3, 7.3.2.1 , 8.11.2.6 , 8.7.4.1.2 , 8.11.3.3
22	18.8, 18.20 , 18.4 , 18.11.2 , 18.11	17.4.2, 4.12.4 , 4.12.2 , 17.5.2 , 19.3.2
23	11.5.3.4, 11.6.6 , 21.7.4.2 , 11.9.9.2 , 21.1.5.4	6.1.1, 6.2.2 , 6.6.3.2.1 , 6.7.2.2.1 , 6.7.2.1.1
24	D.3.2, 8.1.1 , D.3.3.5.4 , 9.2.7 , C.9.2.7	8.7.4.2, 8.4.2 , 8.7.2 , 8.7.5.6 , 8.4.3
25	11.3.2, 11.3.3.2 , 11.1.1 , 11.11.7.2 , 11.5.3.7	18.7.6.2, 18.2.1 , 18.6.4 , 18.8.3 , 18.7.5
26	12, 12.7 , 12.14 , 12.18 , 12.2	14.2.1.3, 11.7.1.1 , 14.2.1.1 , 11.2.1.3 , 13.2.1.1
27	13.6.4.5, 13.3.6.1 , 13.3.1 , 13.7.2.2 , 13.3.8.1	25.5.4.1, 25.5.2.1 , 25.4.7.1 , 25.5.3.1 , 25.5.4.2
28	3.2.2, 5.4.2 , 5.2.3 , 5.11.3.2 , 5.11.3.3	20.2.2.3, 20.6.1.3.1 , 20.4.2.1 , 20.6.1.3.2 , 20.6.1.3.5
29	13.6.4, 13.6.9 , 13.6.5 , 13.6.6 , 13.7.3	17.2.3.5.3, 17.5.3.1 , 17.5.1.2 , 17.5.2.7 , 17.5.2.3
30	3.5.3.5, 3.5.3.6 , 3.5.3.7 , 3.5.4.2 , 3.5.6.1	18.10.1.1, 18.13.3.3 , 18.2.5.1 , 18.2.6.1 , 18.6.1.1
31	21.9.2.1, 21.3.3.1 , 21.3.2 , 21.3.3.2 , 21.3.6.8	22.9.3, 22.8.3 , 22.3 , 25.6.1 , 22.5.3
32	9.5.4.1, 21.9.5.1 , 21.3.6.8 , B.18.8.3 , 16.6.2.3	6.6.1, 6.3.1 , 6.7.1 , 6.8.1 , 6.6

4.3.1.1 Association Between Semantic and Structural Clusters

The association between clusters identified through the various methods presented here can be investigated utilizing Cramer's V statistic (introduced in Section 4.2.4). Table 4.16 and Table 4.17 show the symmetric association matrices for ACI 318-11 and ACI 318-14 clusters. Results are similar across both versions; a) structural clustering (GN 33, see Section 4.2.4) has the greatest association with chapters, b) GPT3 clusters are moderately associated with chapters, c) GPT3 clusters have the greatest average association with other clustering methods, d) associations are generally slightly greater in ACI 318-11 than in ACI 318-14, and e) spaCy clusters have poor associations in all cases.

Table 4.16 ACI 318-11 Cluster Association Matrix

	Chapter	**GN 33**	**spaCy**	**GPT3**
Chapter	1	0.791	0.260	0.584
GN 33	0.791	1	0.242	0.442
spaCy	0.260	0.242	1	0.323
GPT3	0.584	0.442	0.323	1

Table 4.17 ACI 318-14 Cluster Association Matrix

	Chapter	**GN 33**	**spaCy**	**GPT3**
Chapter	1	0.745	0.207	0.566
GN 33	0.745	1	0.211	0.413
spaCy	0.207	0.211	1	0.391
GPT3	0.566	0.413	0.391	1

4.3.2 Semantic Similarity Between Provisions

Semantic similarity was measured between provisions by finding the cosine angle between the provisions' respective embeddings. Each language model constructs the provisions' embedding in a slightly different way, discussed in detail in Section 2.6. For each token in the input text, spaCy identifies a pre-indexed vector and then averages all the vectors (mean pooling) to represent the input text. For all input text to the spaCy model, stop words and words without an index (represented by a zero vector) were removed. GPT3 begins similarly with some index but then uses a predictive model to encode context based on the entire input before averaging the vectors. GPT3 was pre-trained on similarity tasks, essentially meaning it was provided pairs of sentences labeled 'similar' or 'dissimilar' and adjusted the embedding encoding parameters to improve the model's ability to predict the label between pairs.

To visually assess the model against provision locations within the standard, matrix heatmaps and score distributions created using the spaCy model are shown for ACI 318-11 in Figure 4.33 and Fig**ure** 4.34 and for ACI 318-14 in Figure 4.37 and Figure 4.38. Similarity results using the spaCy model are murky and do not appear to measure semantic relations between provisions with any fidelity. This visually confirms results showing low associations between spaCy and chapter titles from Table 4.16 and Table 4.17. The GPT3 model results for ACI 318-11 are shown in Figure 4.35 and Figure 4.36 and for ACI 318-14 in Figure 4.39 and Figure 4.40. The model produces similarity scores with greater intra-chapter scores than inter-chapter scores, with fuzzy lines of demarcation evident on matrix heatmaps for both ACI 318-11 (Figure 4.35) and ACI 318-14 (Figure 4.39). These results again visually affirm results from Section 4.3.1.1, with GPT3 showing moderate association with provision parent chapters. Across all heatmaps, chapter titles appear dissimilar to most other provisions. These likely account for the lower scores in the distributions, which appear to be gaussian mixtures of two or more groups.

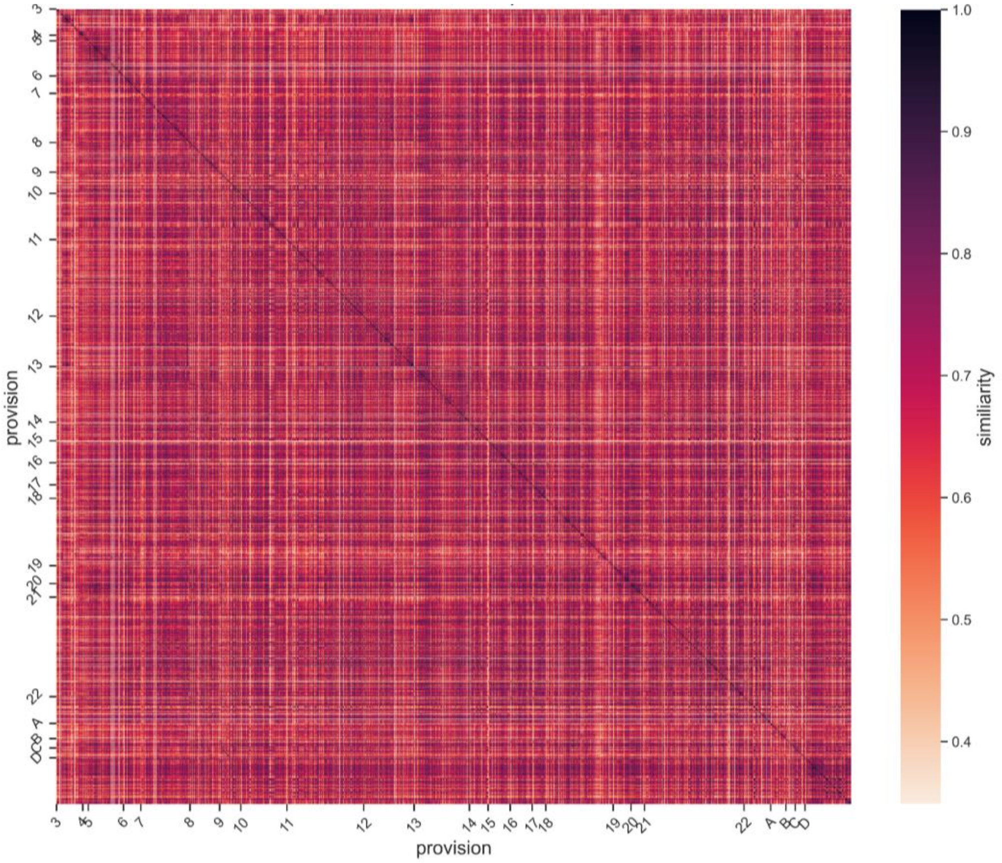


Figure 4.33 ACI 318-11 cosine similarity (spaCy) between all provisons. Chapter titles appear dissimilar to most other provisions. Color scale is optimized for contrast.

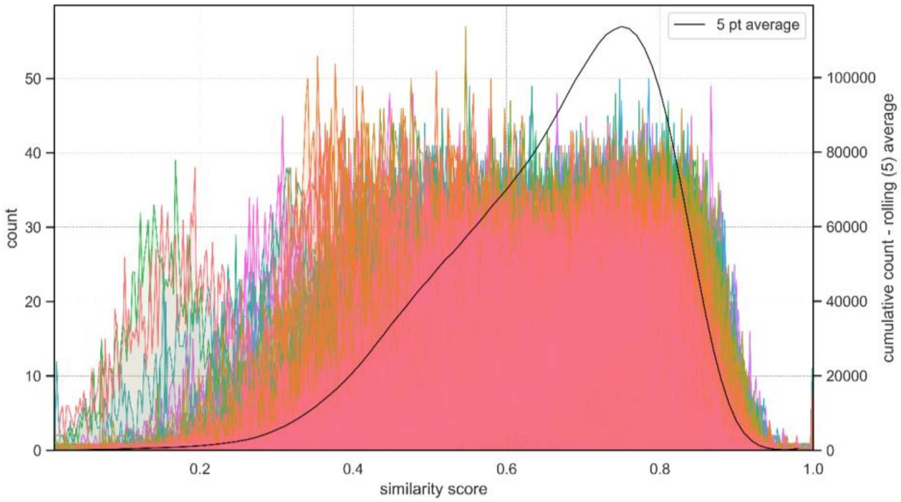


Figure 4.34 ACI 318-11 all-pairs similarity score distribution (spaCy).

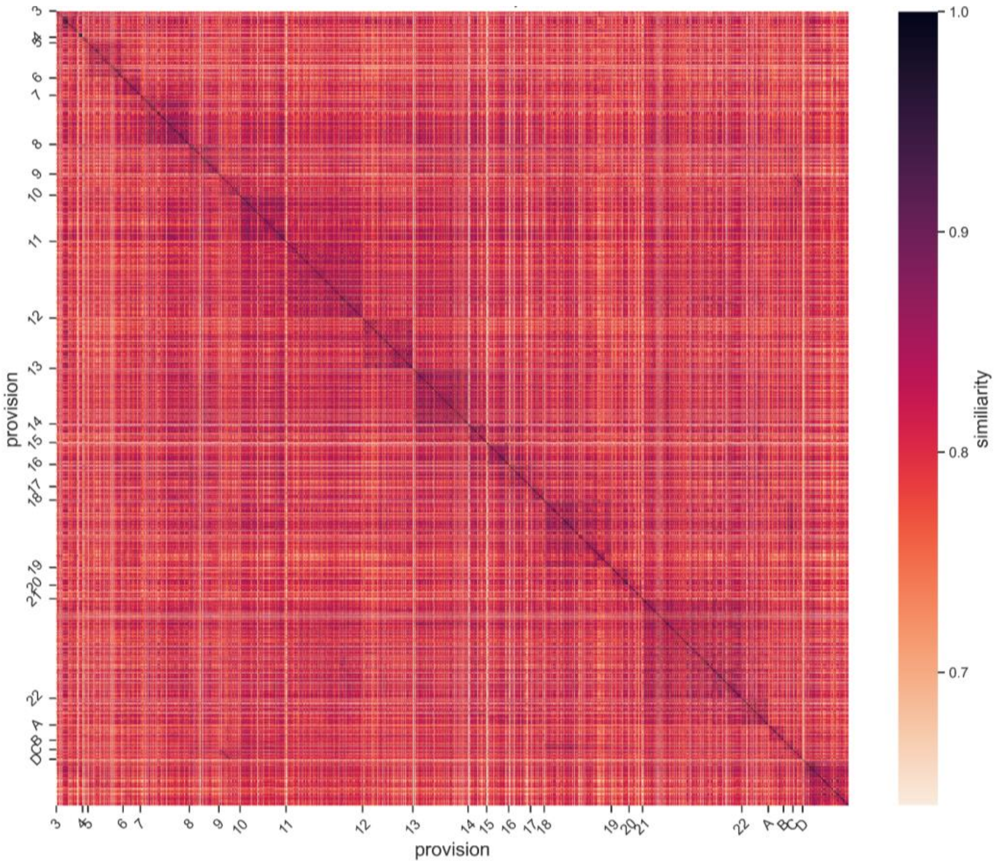


Figure 4.35 ACI 318-11 cosine similarity (GPT3) between all provisions. By inspection, provisions within chapters tend to have greater similarity scores. Chapter titles appear dissimilar to most other provisions. Color scale is optimized for contrast.

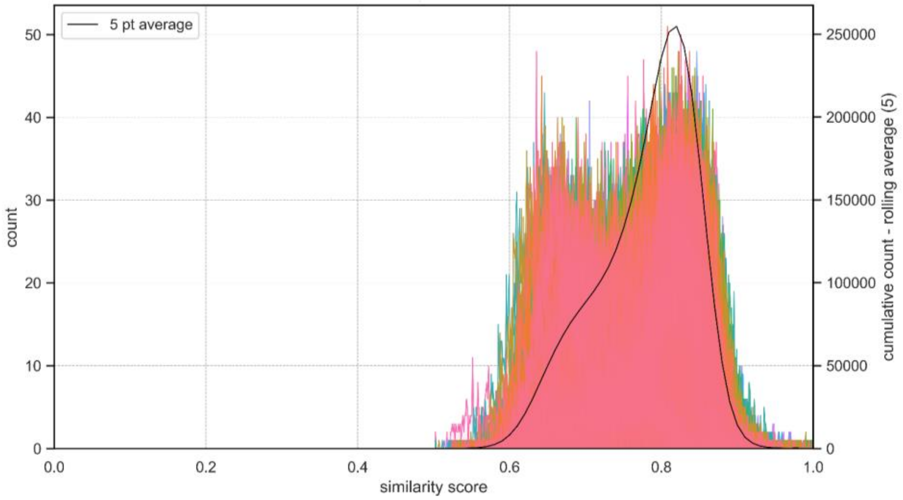


Figure 4.36 ACI 318-11 all-pairs similarity score distribution (GPT3).

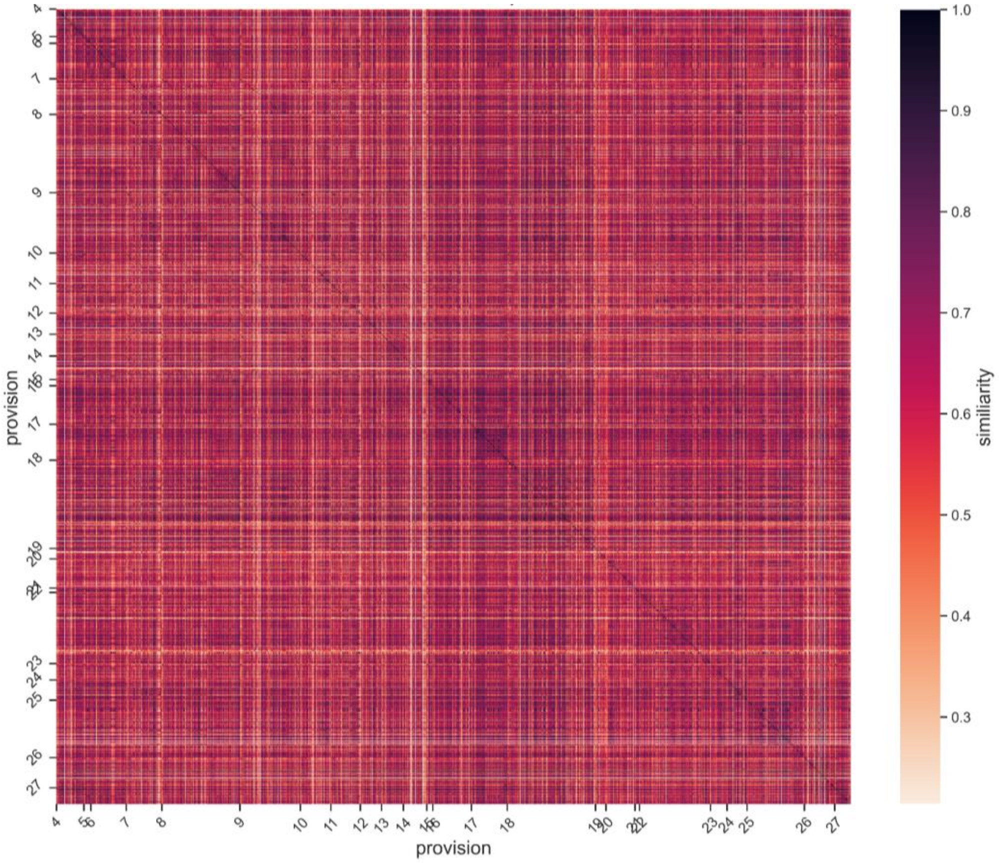


Figure 4.37 ACI 318-14 cosine similarity (spaCy) between all provisons. Color scale is optimized for contrast.

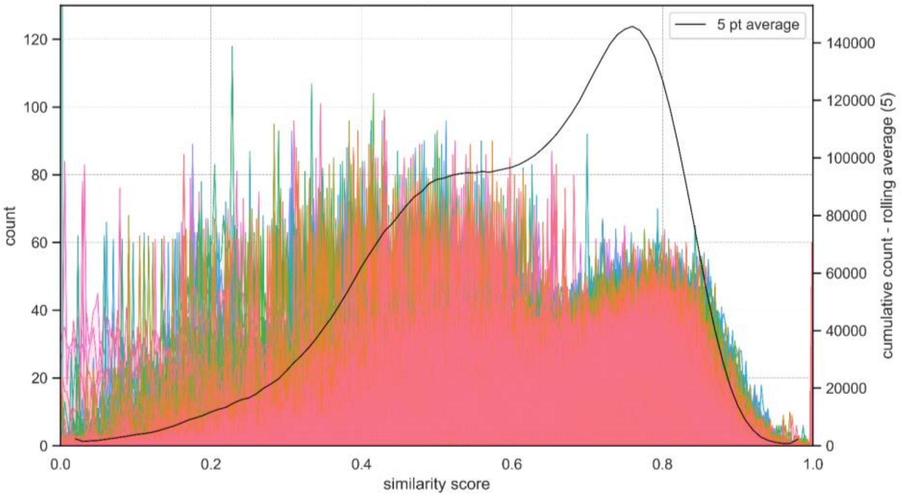


Figure 4.38 ACI 318 -14 all-pairs similarity score distributions (spaCy)

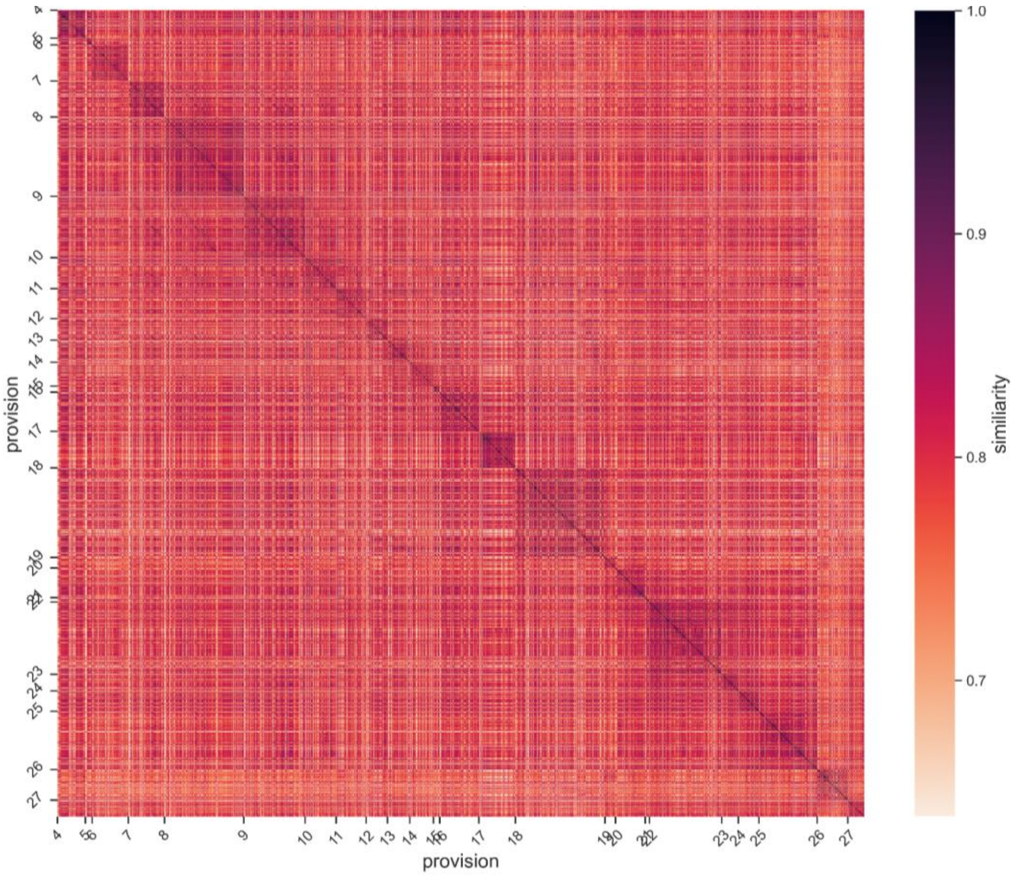


Figure 4.39 ACI 318-14 cosine similarity (GPT3) between all provisions. By inspection, provisions within chapters tend to have greater similarity scores. Chapter titles appear dissimilar to most other provisions. Color scale is optimized for contrast.

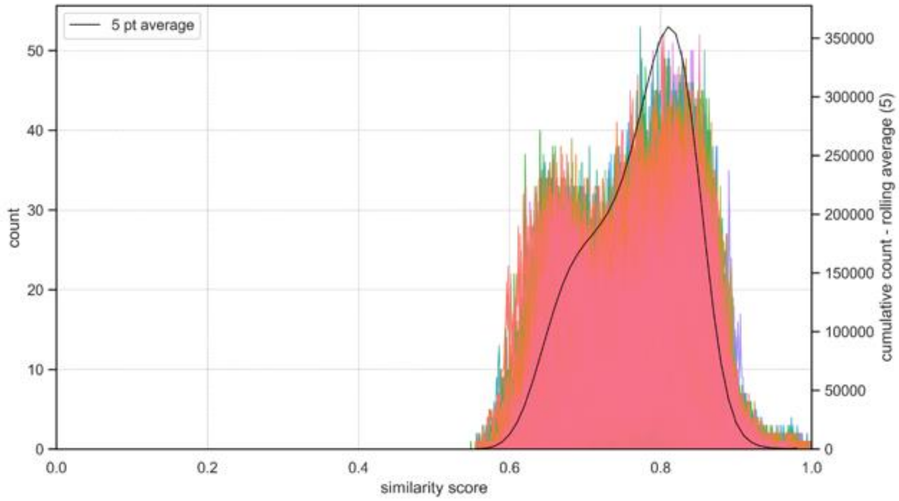


Figure 4.40 ACI 318-14 all-pairs similarity score distributions (GPT3)

4.3.3 Pseudo-Assortativity by Semantic Similarity.

A natural line of inquiry is whether the provisions in each network are more likely to connect to semantically similar provisions. This is a question of assortativity, yet assortativity is typically calculated for nominal or categorical labels *describing nodes* while semantic similarity and path length are distance measurements, *describing a relation between nodes.* Semantic similarity and geodesic path length can be thought of as properties of an imaginary edge (since it may or may not actually exist in the network) between nodes. Assortativity reports whether like nodes are expected to share an edge, but pseudo-assortativity (for lack of a better descriptor) reports whether like edges are expected to share a node pair.

Traditional assortativity utilizes the Pearson correlation, but since the distributions of semantic similarity and the geodesic path distances between each node pair are not normal in either network, the Pearson, Spearman, and Kendall's Tau correlations are all calculated. Kendall's Tau is typically used for relations between discrete ordered data, such as path lengths. Node pairs without geodesic paths between them are excluded from the analysis. 1000 'random' synthetic networks were generated using the directed configuration model to determine if the real networks are pseudo-assortative. The original graph's nodes, as well as their in-degree and out-degree, were preserved in each synthetic network. Synthetic networks were verified to be connected and non-isomorphic with any other synthetic network in the pool. Finally, the correlations between semantic similarity and geodesic path lengths were calculated for all networks.

Results in Table 4.18 show that for both versions of ACI 318, the synthetic networks display a slightly positive correlation between geodesic distance and semantic similarity. Meaning semantically similar provisions are expected (slightly) to be *further apart* than semantically dissimilar provisions. Synthetic networks generated following ACI 318-14's structure show a slightly lower correlation than ACI 318-11 (using GPT3 similarity), possibly indicating a structural improvement to the standard network. Though the characteristic path length (mean geodesic) is also shorter in ACI 318-11 than in ACI 318-14. For both standards, the real networks demonstrate an improvement over synthetic networks by decreasing geodesic path distances between semantically similar provisions, on average. However, the improvements over random in ACI 318-11's real network are slightly greater in magnitude in all cases than that of ACI 318-14, which could be interpreted as a greater necessary 'corrective' or 'compensatory' action in a structure that is inherently less likely to have efficient geodesic paths between related provisions.

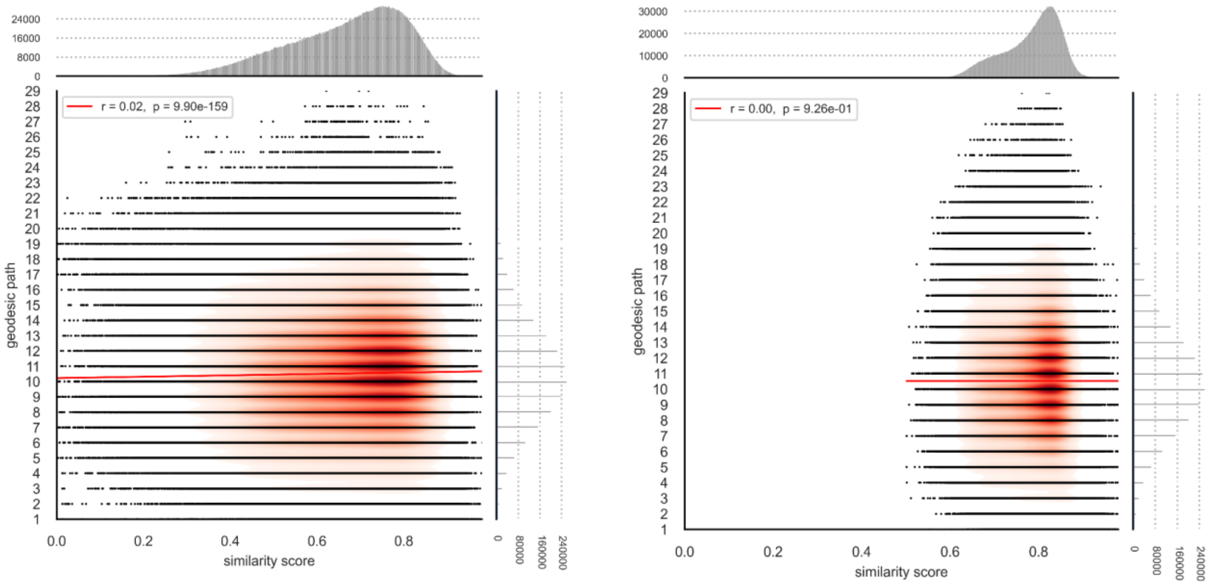
Table 4.18 Pseudo-assortativity by embedding similarity.
(real/random ± standard deviation)

	ACI 318-11		ACI 318-14	
	GPT3	**spaCy**	**GPT3**	**spaCy**
Pearson	0.000/ 0.124 ± 0.007	0.018/ 0.108 ± 0.008	0.023/ 0.090 ± 0.0056	0.062/ 0.112 ± 0.0077
Kendall's Tau	0.008/ 0.095 ± 0.005	0.018/ 0.082 ± 0.006	0.022/ 0.073 ± 0.0039	0.048/ 0.086 ± 0.0053
Spearman	0.012/ 0.134 ± 0.007	0.027/ 0.115 ± 0.008	0.032/ 0.102 ± 0.0054	0.071/ 0.121 ± 0.0075

Similarity scores and geodesic path distances are plotted against each other for ACI 318-11 in Figure 4.41 and for ACI 318-14 in Figure 4.42**.** The trendline that derives the Pearson coefficient is shown in each plot. GPT3 is likely the best semantic representation of the standard, and comparisons between ACI 318-11 and ACI 318-14 show that semantically related provisions are closer to one another in the older version of ACI 318, by a slight margin (also evident in Table

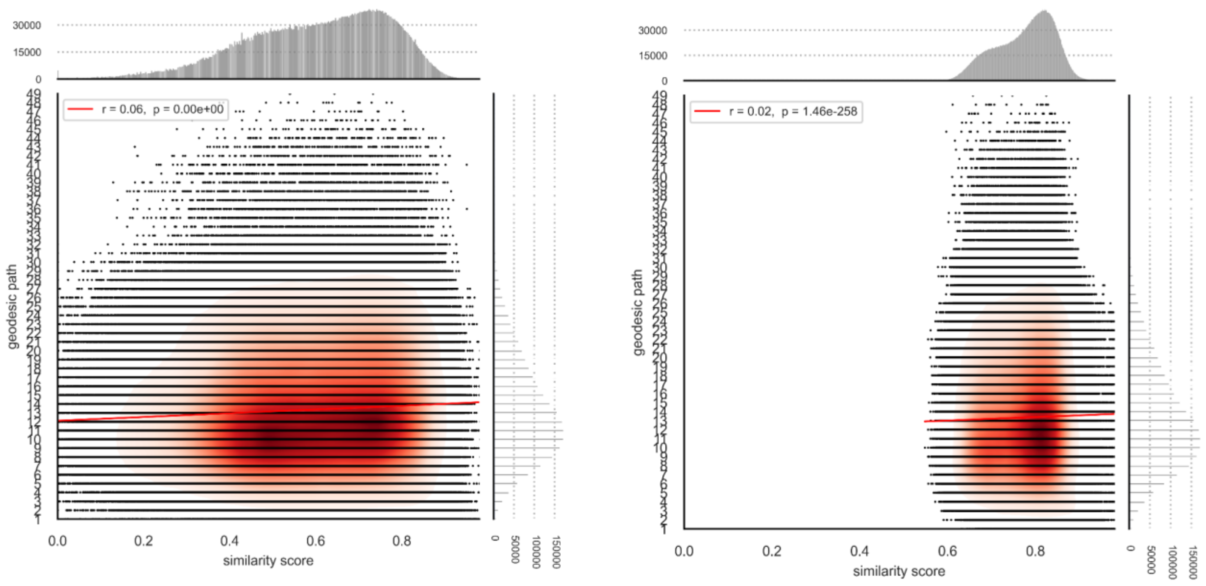
4.18. This may mean that an amenable structure requires intelligently restricting of connectivity (modularity) as much as it requires enabling logical flows (hierarchy) through the standard.

This analysis is limited by the shortcomings of the natural language models[†] described in Section 4.3. Additionally, the similarity score distributions appear to be mixtures (potentially Gaussian), which could be parsed into separate distributions by further analysis to facilitate more representative results. The natural language models are likely biased by the structure of the provision (whether it be a title or paragraph form) and separating these is likely to improve results of this analysis.



(a) spaCy similarity **(b) GPT3 similarity**

Figure 4.41 ACI 318-11 similarity scores vs geodesic paths lengths.



(a) spaCy similarity **(b) GPT3 similarity**

Figure 4.42 ACI 318-14 similarity scores vs geodesic path lengths.

4.4 Chapter Summary

In Chapter 4, network representations of standards are developed and analyzed to better understand the important relationship between the structure and presentation of design standards and navigational complexity. The reference networks of two versions of ACI 318, 2011 and 2014, were compared under the assumption that ACI 318-14 is structurally improved over its predecessor. The study included analyzing the networks' characteristic features, centrality metrics, clustering tendencies, recurring motifs, and geodesic paths, as well as enriching the networks with semantic embeddings to investigate the relationship between structural features and meaning. The analyses aimed to identify useful metrics of navigational complexity based on network structure and link them to end-users' perceptions of the standards’ quality.

The networks’ features are similar, which allows for justifiable comparisons across many metrics. Common centrality metrics, which measure importance based on atypical connectivity, were found to be somewhat useful in identifying both important groups of nodes and potentially problematic groups of nodes. Many node groups with high centrality scores in ACI 318-11 were revised in ACI 318-14. Some centrality distributions may be useful in measuring the effects of explicit references on the network and the health of the implicit network, by proxy.

Assortative mixing refers to the tendency of nodes to connect with others that share similar attributes, such as metadata or node properties. The degree assortativity coefficient measures the correlation between the degrees of connected nodes, with values ranging from -1 to 1. The degree assortativity for the implicit and complete reference networks of ACI 318-11 and ACI 318-14 all tend towards being slightly assortative by degree. However, explicit references decrease assortativity in ACI 318-14 and marginally do so in ACI 318-11, indicating that explicit edges tend to connect nodes with dissimilar degrees. Nodes with similar degrees may share similar roles, such as introductory provisions with many sub-sections or detailing provisions without sub-sections.

Clustering and motifs, which are closely related, were analyzed for the ACI 318-11 and ACI 318-14 complete and implicit reference networks. The clustering coefficient, which measures the density of subgraph triangles in the networks, was compared between the two standards' networks. ACI 318-14's implicit and complete networks have a higher concentration of nodes with a clustering score of zero, indicating they are leaf nodes and only referenced implicitly. Motifs, which are overexpressed connection patterns forming subgraphs of 3 or more nodes, were identified using the open-source software mFinder. The concentration of cyclic subgraphs with 3 nodes decreased from ACI 318-11 to ACI 318-14, but some circular referencing structures nonetheless remain. The remaining structures were not investigated to determine if they are functionally necessary or potentially detrimental. 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 substantially greater than those occurring in ACI 318-14. This analysis indicates that further research into identifying and eliminating unnecessary motifs (and their functions) could improve the consistency of the standard and the user experience.

The geodesic (shortest) paths between provisions in both versions of ACI 318 implicit, explicit, and complete networks were found and visualized using heatmaps. The implicit reference networks connect in the 'forward' direction, populating only the portion of the matrix above the main diagonal. The triangular 'skylines' to the right of the main diagonal indicate the relative number of provisions in each chapter and subchapters. The explicit reference networks reach both forward and backward but are sparse. The complete reference networks exhibit traits from their constituent networks but also emergent properties. Moving vertically through the complete network heatmaps, ACI 318-14 appears less homogeneous than ACI 318-11, a possible reflection of specialized chapters and a modular hierarchy. Grey horizontal 'bands' in these figures, broken only near the main diagonal, indicate that the provisions are only reachable along the implicit path or by 'direct' explicit references. These bands are constituted predominantly of nodes with low clustering scores. ACI 318-11 relies heavily on references to earlier provisions in the document, as seen by the darker regions below the main diagonal. End-users may find this disrupting to the implicit flow of the standard.

The ACI 318 revision aimed to reorganize the standard to match the end-users' mental maps of the design space, and thereby reduce navigational complexity. However, stakeholders have different mental maps and current standard writing may preclude the mind-mapping of many of these stakeholders. Natural language models, such as GPT3, can potentially aid in presenting standards in a way that matches the end-user's mental map. To this end, this research explored the spatial relations between provisions in both versions of ACI 318 using structural network clustering methods and spatial clustering methods on vector embeddings.

The Girvan-Newman algorithm was used to find clusters in both compete networks using edge betweenness centrality. Analysis found that the modularity score was maximized for both complete networks at 33 clusters. The k-means clustering algorithm was used to cluster provisions into groups based on their location in the embedding space. Silhouette analysis and k-means clustering results were presented for both versions of ACI 318, using spaCy and GPT3 embeddings. For each standard, the three clustering methods were compared with each other and with the provision's parent chapter. Structural clustering was found to have the best association with the parent chapters, based on the implicit hierarchy. GPT3 embeddings performed moderately well and could likely be improved with an alternative clustering algorithm or parameters. Provisions that fall outside of their parent chapters' dominant clusters found by structural and semantic clustering methods could be investigated as being potentially misplaced or having atypical references.

Finally, correlations between semantic similarity and geodesic path length were investigated by modifying traditional assortativity to measure correlations between edge properties of a node pair, instead of node properties. The results of the pseudo-assortativity analysis indicate that both versions of ACI 318 have shorter geodesic paths between semantically similar node pairs than would be expected in networks generated randomly using the configuration model. The geodesic paths are marginally shorter, on average, between similar nodes in ACI 318-11, though the mean geodesic is also shorter. These results may indicate that over-connectivity, or non-prudent referencing to nodes shallow in the hierarchy, is detrimental to user-experience.

5.0 Analysis of ISO 22156

The International Organization for Standardization (ISO), in an initiative lead by the International Network for Bamboo and Rattan (INBAR), published the first series of international full-culm bamboo mechanical characterization and structural design standards in 2004 (ISO 2004a, ISO 2004b, ISO 2004c). A volunteer group of bamboo specialists from Asia, Latin America, Europe, and the United States prepared draft documents and with 14 national standardization bodies “laboriously discussed” them over a 3-day meeting before submitting draft texts to ISO (Janssen 2005). The intent of the bamboo structural design standard, ISO 22156:2004 was to establish a modern limit-state design approach to designing with bamboo while acknowledging and accepting traditional vernacular construction practices (Janssen 2005). The standards were based on traditional knowledge and research developed largely by Janssen (1981) and Arce-Villalobos (1993). Harries et al. (2012) reported that this balance between traditional and modern practice was inadequate for developing regions, since specialized engineering knowledge is needed to apply a modern limit states approach. Traditional knowledge is often insufficient to address ultimate limit states, such as those induced by seismic forces.

Colloquially, ISO 22156-2004 and ISO 22157-2004 could be considered “version zero” (v0) standards. These v0 standards are fundamentally inadequate for performing holistic design for the majority of potential end-users, yet function well as an impetus for collaborative research by developing a lingua franca and exposing gaps in domain knowledge. A v0 document is intended to be revised as new knowledge is generated through research and practice; Janssen (2005) reports that many of the original chapters “only give a general outline”. The drafting committees anticipated revision and considered an accompanying ‘lab manual’ (ISO 22157-2:2004) essential to the success of the ISO 22157-1:2004 material characterization standard, as this could be updated more frequently[16] and “simply explain why this standard is needed and give good examples from practice” (Janssen 2005). In the signal analogy presented by Bulleit (2012) and discussed in Section 2.4, the ISO 22157-2:2004 lab manual is a parallel communication channel that reduces noise in the primary ISO standard. Utilizing this parallel channel adds flexibility to the standard by preserving the intent and known limits of the standard in natural language while leaving opportunities for improvements before the next standard revision.

It would be more than 15 years before a reconstituted ISO bamboo subcommittee (ISO TC 165 WG 12) published revised standards for mechanical characterization, ISO 22157-2019 (2019), and structural design, ISO 22156-2021 (2021). ISO 22156-2021 permits allowable capacity design as well as allowable stress design while preserving the ability to design structures based on local experience from previous generations. Adopting allowable capacity or stress approaches rather than a load and resistance factor (LRFD) or partial safety factor (PSF)[17] approach reflects the still limited engineering knowledge of bamboo and is better aligned with allowing traditional knowledge to inform design, thereby addressing the criticism of Harries et al. (2012). Additionally, the revisions to ISO 22156 were constrained by ISO protocols requiring that the “general format” of the existing ISO 22156-2004 chapters not be significantly changed. Thus, the layout of ISO

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[16] Unfortunately, due to the rigid protocols enforced by ISO, frequent updating is not practical.

[17] LRFD and PSF approaches are fundamentally the same; these are the terminology used in North American and European practice, respectively.

22156 can evolve but not exhibit wholesale change in a single revision. Table 5.1 provides a summary of Chapter titles and the reorganization of ISO 22156:2004 into ISO 22156:2021.

ISO 22156:2021 was selected as a case study because of the rising international interest in structural bamboo, which has led to a corresponding uptick in research to fill knowledge gaps and further improve the standard. This increase in research likely means the standard will be revised again sooner, rather than later, and will have to accommodate new knowledge into its organization. Thus, it is hoped that the analysis described here provides a baseline against which future versions of ISO 22156 may be compared (and improved upon).

Many of the stakeholders in bamboo structural design are fundamentally different than those for conventional engineering materials. The ISO series of bamboo standards (now also including a grading standard, ISO 19624:2019) is aimed squarely at users in the Global South. Authors[18] of the new ISO standards expressed interest in minimizing complexity as a means of making the documents both more accessible and to improve their adoption worldwide (Harries et al. 2020).

The intent of this chapter is to conduct the same analyses on ISO 22156 as was described at length for ACI 318 in Chapter 4. The authors of ISO 22156:2021 attempted to reduce complexity in the standard. The analyses presented tests this claim and will provide guidance and a benchmark for future versions of ISO 22156. Methods of text processing, network generation and network analysis are the same as those presented in Chapter 4. The results for the ISO 22156 analyses are described in this chapter.

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[18] Dissertation supervisor, Professor Harries, was the lead author of ISO 22156:2021. Some of the insights provided in this chapter are based on his ‘inside’ knowledge of both ISO 22156 and the ISO standardization process.

Table 5.1 Chapter level reorganization of ISO 22156:2004 to ISO 22156:2021

ISO 22156:2004		**ISO 22156:2021**		**Comment**
Description	**Chap – Title**	**Description**	**Chap – Title**	
Introductory	1 – Scope	Introductory	1 – Scope	
	2 – Normative references		2 – Normative references	
	3 – Terms and definitions		3 – Terms and definitions	
	4 – Symbols and abbreviated terms		4 – Symbols	
Design	5 – Basic requirements	Design	5 – Basic requirements of design	
	6 – Design concepts		6 – Member component and material properties	includes Ch. 15 from 2004
	7 – Structural design		7 – Structural modelling bamboo structures	combines Ch. 7 and 8 from 2004
	8 – Schematisation	Member – based	8 – Flexural members (beams)	
Member - based	9 – Beams (predominately loaded in bending)		9 – Axial load carrying members	
	10 – Columns (predominately loaded in an axial direction)		10 – Joints and Splices	
	11 – Joints		11 – Trusses	
	12 – Assemblies (trusses)		12 – Shear panels (walls)	
	13 – Panels	Other	13 – Fire resistance	
Other	14 – Reinforcement in concrete and soil[a]		14 – Structural grading	
	15 – Durability and preservation		15 – Quality assessment and control	
	16 – Fire Protection	Basis	Annex A (informative) Bases of provisions in this document	Annex B from 2004
	17 – Grading	Best Practice	Annex B (informative) Durability and preservation recommendations	
	18 – Quality Control	Example	Annex C (informative) Examples of seismic and alternative design factors	New
Basis	Annex A(informative) Background and history[b]		Annex D (informative) Examples and classification of bamboo connections and joints	New
	Annex B(informative) Assumptions		Annex E (informative) Design of LCBF components to satisfy requirements of 12	New
		Reference	Bibliography	

[a] Chapter 14 from 2004 was removed in its entirety; such applications are beyond the scope of ISO 22156 and are ‘ill conceived’ (Archila et al. 2018)

[b] Annex A from 2004 was removed in its entirety.

5.1 Generating Graphs

Using the process described in 4.1, the complete networks for ISO 22156:2004 and ISO 22156:2021, shown in Figure 5.1 and Figure 5.2, respectively, were extracted for analysis. Both networks are considerably smaller than the ACI 318 networks described in Chapter 4. This may limit some statistical analysis and the applicability of some of the insights described in Chapter 4. Additionally, the content of ISO 22156:2021 is significantly more technical and voluminous than that the earlier 2004 version zero; therefore, comparisons between the two versions of the standard are also limited. In both Figure 5.1 and Figure 5.2, motif ID 38, which is strongly expressed in ACI 318, also appears to be a motif in these networks; this is statistically investigated in 5.2.3.

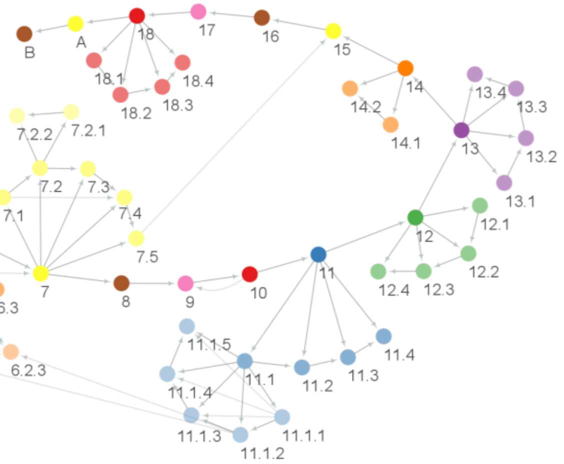


Figure 5.1 ISO 22156:2004 complete reference network. All provisions are labeled and chapters are colored only for clarity. Explicit and implicit references are represented by grey arrows. Nodes with greater translucency are deeper in the hierarchy. Layout is based on the implicit network.

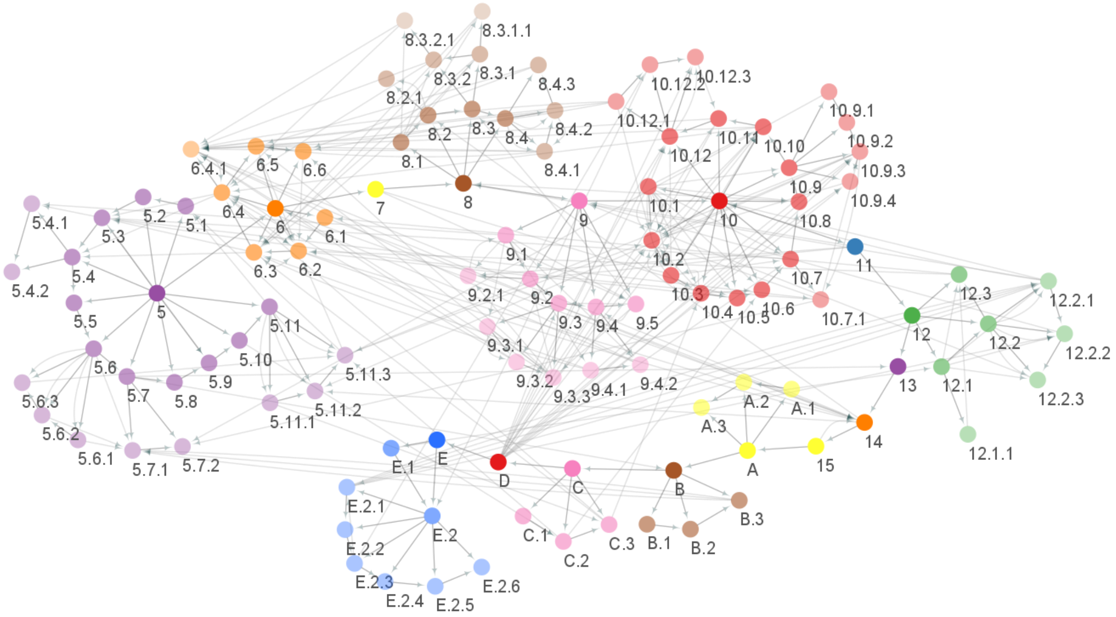


Figure 5.2 ISO 22156:2021 complete reference network. All provisions are labeled and chapters are colored only for clarity. Explicit and implicit references are represented by grey arrows. Nodes with greater translucency are deeper in the hierarchy. Layout is based on the implicit network.

5.2 Network Features

As discussed in Chapter 4, graphs and networks are high-level abstractions and it is not immediately clear which extracted metrics may be related to navigational complexity. Here, centrality, clustering, and geodesic paths are used to describe the connectivity of ISO 22156:2004 and ISO 22156:2021. Implicit and complete reference networks are sometimes considered separately to understand effects of explicit references on connectivity in each of the networks. Table 5.2 summarizes the basic features of the networks of ISO 22156:2004 and ISO 22156:2021, as well as some of the connectivity features extracted; the latter are described in the following sections. In comparison to both ISO 22156:2004 and ACI 318, ISO 22156:2021 has a greater proportion of explicit nodes and edges, possibly indicating compensation for a poor implicit structure or excessive explicit referencing potentially detrimental to user experience. This hypothesis is substantiated, assuming forward flow is important to navigation, by the single largest strongly connected[†] component present in ISO 22156:2021, containing 86% of nodes. All nodes can reach each other using directed edges in strongly connected components, likely meaning ‘flow’ in the network is not well directed and the implicit hierarchy (mental map) is not maintained.

Table 5.2 ISO 22156:2004 and ISO 22156:2021 digraph feature summary

	ISO 22156:2004	ISO 22156:2021
Nodes	57	111
Edges	100	361
Implicit Edges (% of total edges)	86 (86%)	176 (49%)
Explicit Edges (% of total edges)	14 (14%)	185 (51%)
Explicit Direction (Forward: Backward)	(11:3)	(68:117)
Explicit Active Nodes (% of total nodes)	18 (32%)	91 (82%)
Largest Strong Component Fraction	0.035	0.864
Average Degree	3.5	6.5
Characteristic Path (mean geodesic)	4.0	5.7
Diameter (longest geodesic)	12	14
Degree Assortativity – implicit (jackknife error)	-0.221 (0.213)	-0.107 (0.097)
Degree Assortativity – complete (jackknife error)	-0.050 (0.293)	0.179 (0.169)
Clustering C (mean/median)	0.281/0.333	0.209/0.167
Average Node Depth in Implicit Hierarchy	2.26	1.89
Pages in PDF	19	56

5.2.1 Centrality Metrics

The centrality of a node is a measure of its importance to the network, based on some connectivity properties. As discussed in Section 4.2.1, clusters of nodes with high centrality may also be areas of the standard worth inspecting for organizational issues. Common centrality metrics for each version of ISO 22156 are explored in the following sections. Each centrality analysis is presented with a distribution of the centrality metric across the networks as well as the 5 nodes rated as most central by the algorithms. Deviations from each mean centrality score are visualized in the summary Section 5.2.1.6.

5.2.1.1 Degree Centralities

Three degree distributions are observed for directed graphs: the total-degree (Figure 5.3), in-degree (Figure 5.4), and out-degree (Figure 5.5) distributions. Neither ISO 22156:2004 or ISO 22156:2021 display log-normal degree distributions and neither are considered scale-free. The total-degree distribution of ISO 22156:2021 displays a heavy tail with positive skew, driven by outgoing references. The majority of real networks display an exponential decay from the peak distribution, however the decay for ISO 22156:2021 appears almost linear and accounts for the significant increase in the mean degree between the two standards. In Section 4.2.1.1, it appeared that smoothing the distribution improved navigation, however the analysis here may indicate the limits of that guidance, as the distribution itself is significantly different from typical network degree distributions. The result is an increased mean degree, significantly greater than that of the much larger ACI 318 networks. This may indicate decreased modularity and unclear provisional navigation functions (i.e. many provisions appear to behave as pointers).

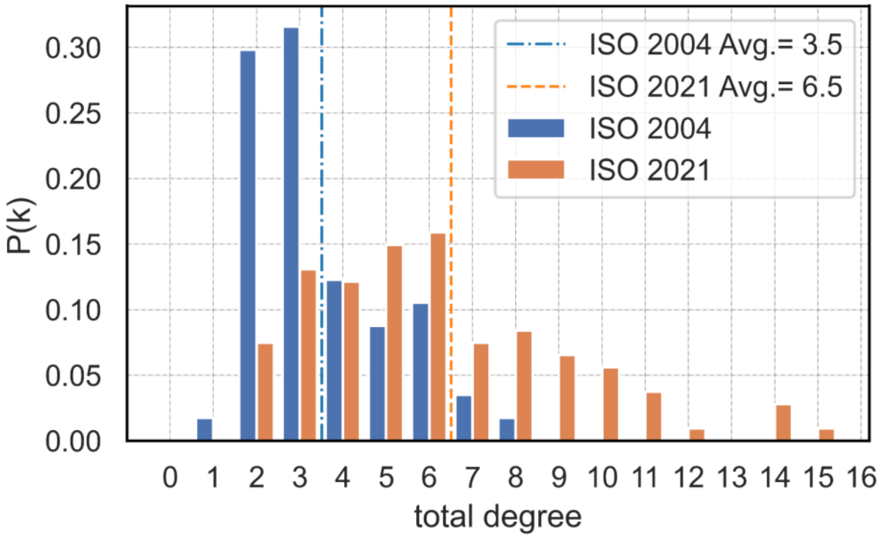


Figure 5.3 ISO 22156 complete networks total-degree distribution.

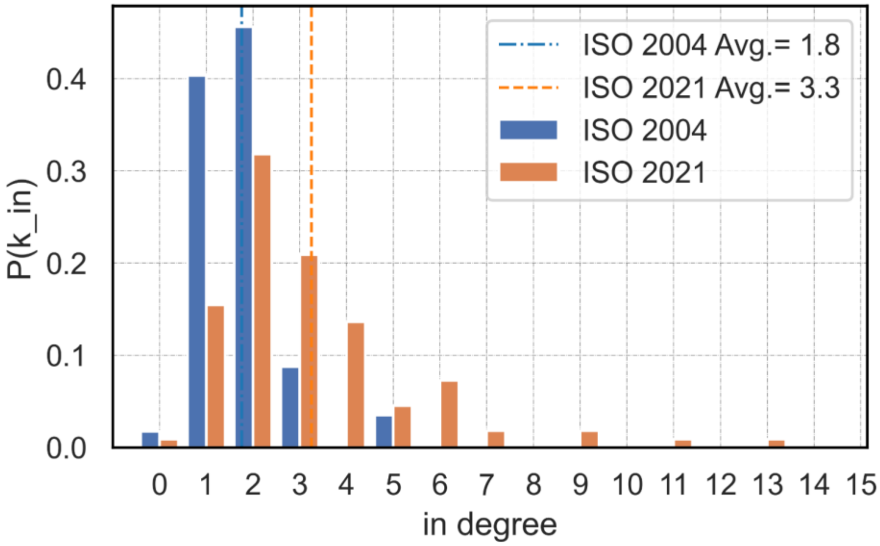


Figure 5.4 ISO 22156 complete networks in-degree distribution.

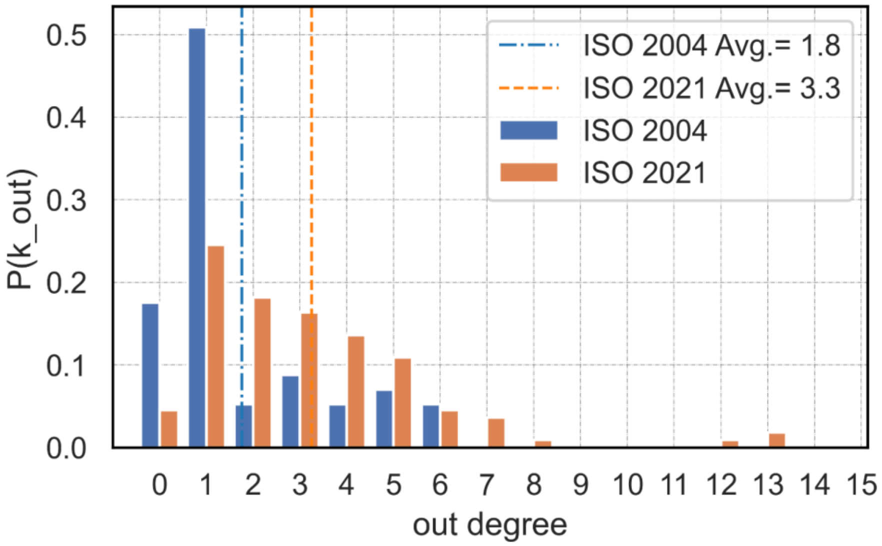


Figure 5.5 ISO 22156 complete networks out-degree distribution.

Degree appears to be associated with the relative ‘importance’ of some provisions in the design process in ACI 318. Although again it is impossible to objectively discern which provisions are more important to design, nodes representing unique wrinkles in the design workflow using ISO 22156:2021 are represented in the highest scoring nodes shown Table 5.3. Shown are provisions covering joint characterization and design as well as the provision governing allowable strength design of members.

Table 5.3 Top in/ out-degree nodes (counts) for ISO 22156

	ISO 22156:2004 Implicit	ISO 22156:2004 Complete	ISO 22156:2021 Implicit	ISO 22156:2021 Complete
Total-degree	7 (7) 11.1 (7) 5 (6) 6.2 (6) 11 (6) 12 (6) 13 (6) 18 (6)	7 (8) 6.2 (7) 11.1 (7) 5 (6) 6.2.2 (6) 11 (6) 12 (6) 13 (6) 18 (6)	10 (14) 5 (12) 6 (8) E.2 (8) 9 (7) 10.9 (7)	10.2 (17) D (17) 6.4.1 (16) 10 (16) 6.4 (15)
in-degree	30 tied at 2	6.2.2 (5) 6.2.3 (5) 6.2 (3) 7.4 (3) 11.1.3 (3) 11.1.4 (3) 11.1.5 (3)	67 tied at 2	10.2 (16) 6.4.1 (13) 6.2 (11) 6.3 (9) 6.4 (9)
out-degree	10 (13) 5 (12) 6 (7) 9 (6) E.2 (6)	5 (6) 7 (6) 11.1 (6) 11 (5) 12 (5) 13 (5) 18 (5)	10 (13) 5 (12) 6 (7) 9 (6) E.2 (6)	D (16) 10 (13) 10.1 (13) 5 (12) 5.6 (8)

5.2.1.2 PageRank Centrality

PageRank centrality distributions for the complete ISO 22156:2004 and ISO 22156:2021 networks are shown in Figure 5.6. Centrality scores for ISO 22156:2021 appear concentrated near lower scores (more so than ISO 22156:2004), but this is likely an effect of the scale of the networks. PageRank centrality scores sum to unity across each network (see Eq. 4.1), so the number of nodes in a network and the average centrality score share an inverse relationship. Table 5.4 shows the 5 top-ranked nodes in each implicit and complete ISO 22156 network, as determined from PageRank centrality. In the ISO 22156:2021 complete network, PageRank identified those nodes with high out-degree and relatively low out-degree as being important. Unlike the top provisions found for ACI 318, these provisions are essential to design and would nearly all be used in a design instance. Equally, there are many commonly used provisions that are not found to be important by this metric.

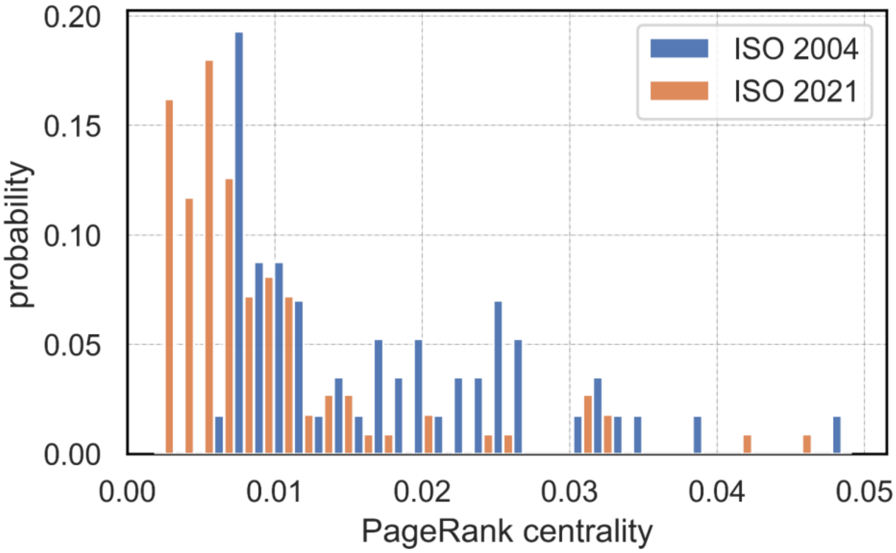


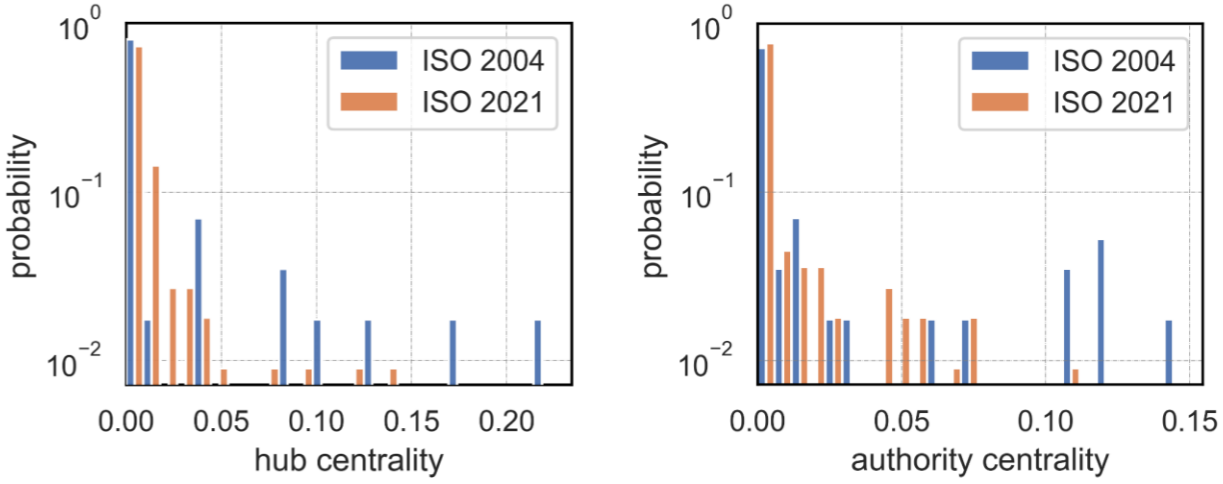
Figure 5.6 ISO 22156 complete networks PageRank centrality distributions.

Table 5.4: PageRank top nodes (scores) for ISO 22156:2004 and ISO 22156:2021

ISO 22156:2004 Implicit	ISO 22156:2004 Complete	ISO 22156:2021 Implicit	ISO 22156:2021 Complete
18.4 (0.0364)	6.2.3 (0.0491)	E.2.6 (0.0218)	6.2 (0.0457)
11.1.5 (0.0328)	18.4 (0.0392)	E.2.5 (0.0194)	14 (0.0414)
5.5 (0.0307)	18 (0.0350)	5.11.3 (0.0185)	6.4 (0.0323)
11.4 (0.0302)	17 (0.0337)	10.9.4 (0.0183)	10.2 (0.0316)
18.3 (0.0294)	16 (0.0321)	10.12.3 (0.0173)	10.3 (0.0311)

5.2.1.3 HITS Centrality – Hubs and Authorities

The HITS hub and authority centrality distributions for the ISO 22156 complete networks are shown in Figure 5.7. These distributions give little information into the structure of the network. Clusters of nodes with high centrality in ACI 318-11 tended to point to areas of high revision. In ISO 22156:2021, high scores appear clustered around Chapters 10 and 6, as well as Appendix D (Table 5.5). The content of these sections was almost entirely new to ISO 22156:2021. Chapter 10 and Appendix D are both related to connections, and are therefore somewhat self-contained. Chapter 6 defines allowable force and stresses used throughout the remaining chapters. As discussed in Section 4.2.1.3, HITS is not identifying 'important' hubs and authorities so much as it is identifying atypical referencing between provisions, potentially highlighting areas that have special function but also those potentially in need of reorganization or revision. The greater HITS centrality within the new provisions of ISO 22156:2021 likely indicates that their drafting appears to differ somewhat from other provisions in the standard, more than their importance to the standard.



a) hub centrality b) authority centrality

Figure 5.7 ISO 22156 complete networks HITS centrality

Table 5.5 HITS centrality top nodes (scores) for ISO 22156:2004 and ISO 22156:2021

	ISO 22156:2004 Implicit	**ISO 22156:2004 Complete**	**ISO 22156:2021 Implicit**	**ISO 22156:2021 Complete**
Hubs	11.1 (0.424) 11 (0.228) 11.1.1 (0.0686) 11.1.2 (0.0686) 11.1.3 (0.0686)	11.1 (0.2230) 11.1.1 (0.1756) 11.1.2 (0.1328) 6.2 (0.1030) 5.5 (0.0813)	10 (0.5197) 10.9 (0.0600) 10.7 (0.04368) 10.2 (0.04030) 10.1 (0.04030)	10 (0.1387) 10.1 (0.1216) D (0.0901) 10.3 (0.0743) 10.4 (0.0519)
Authorities	11.2 (0.1617) 11.1.2 (0.1222) 11.1.3 (0.1222) 11.1.4 (0.1222) 11.1.5 (0.1222)	11.1.3 (0.1472) 11.1.4 (0.1222) 11.1.5 (0.1222) 6.2.3 (0.1222) 11.1.2 (0.1104)	10.10 (0.077) 10.8 (0.075) 10.2 (0.075) 10.3 (0.075) 10.4 (0.075) ...	10.2 (0.1108) 10.12 (0.0747) 10.10 (0.0720) 10.7 (0.0702) 10.4 (0.0561)

5.2.1.4 Betweenness Centrality

The distributions for ISO 22156:2021 and ISO 22156:2021 complete networks are presented in Figure 5.8. Nodes with high betweenness scores appeared to represent some provisions that are common to many design instances in ACI 318. This trend is consistent with the centralities found in the ISO 22156:2021 complete network as well. Because there are so few explicit references in ISO 22156:2004, they have a limited effect on betweenness centrality in the complete network.

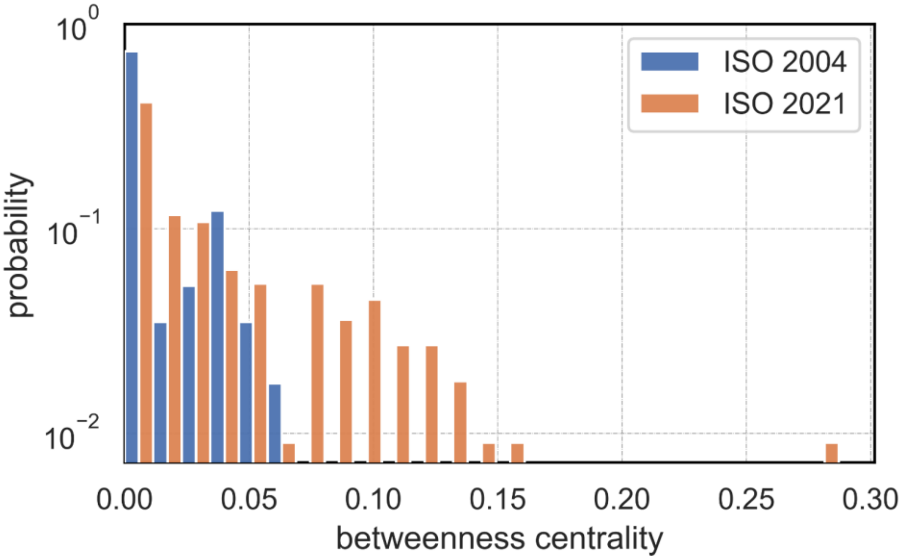


Figure 5.8 ISO 22156 complete networks betweenness centrality.

Table 5.6 Betweenness top nodes (scores) for ISO 22156:2004 and ISO 22156:2021

ISO 22156:2004 Implicit	ISO 22156:2004 Complete	ISO 22156:2021 Implicit	ISO 22156:2021 Complete
11 (0.0623)	11 (0.0623)	10 (0.0225)	14 (0.2872)
10 (0.0536)	10 (0.0532)	9 (0.0220)	6.4.1 (0.1511)
12 (0.0500)	15 (0.0467)	8 (0.0198)	6.2 (0.1402)
9 (0.0441)	12 (0.0441)	A (0.0192)	10.3 (0.1350)
13 (0.0441)	16 (0.0441)	12 (0.0187)	5.3 (0.1330)

5.2.1.5 Closeness Centrality

Closeness centrality distributions for the implicit ISO 22156 networks are shown in Figure 5.9. ISO 22156:2004 (kurtosis = 1.30, skew = -0.56) and ISO 22156:2021 (kurtosis = 0.59, skew = -0.15) are well represented by normal distributions. The mean of the complete ISO 22156:2004 (kurtosis = 3.00, skew = 1.17) network changes very little, although the distribution skews more positive and kurtosis increases (trends also seen in ACI 318-14). The ISO 22156:2021 (kurtosis = 1.06, skew = 0.35) complete network shows a much larger increase in mean than any other network investigated in this research, indicating a more significant effect from explicit references. Closeness centrality scores for the ISO 22156:2021 complete network are shown in Table 5.7 and appear representative of provisions users might find important for design.

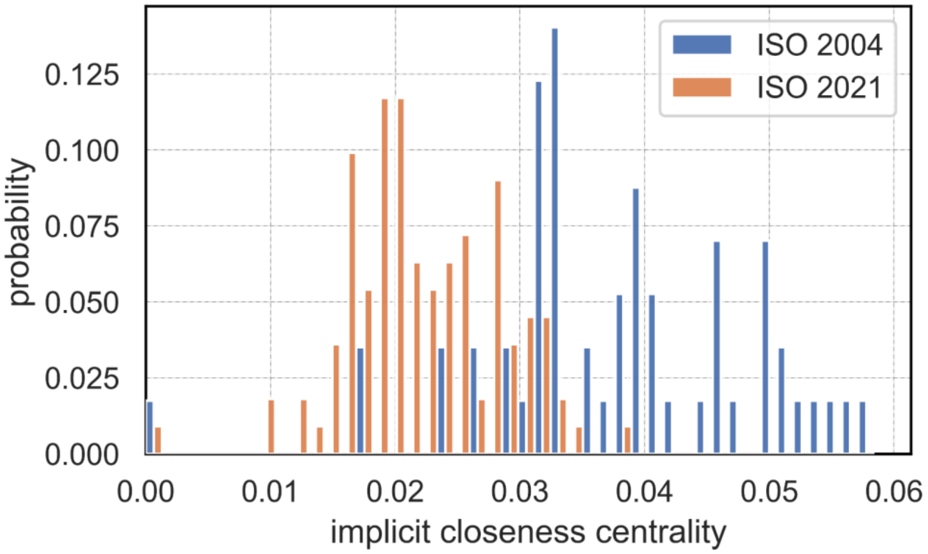


Figure 5.9 ISO 22156 implicit networks closeness centrality.
means: ISO 22156:2004 = 0.038, ISO 22156:2021 = 0.022

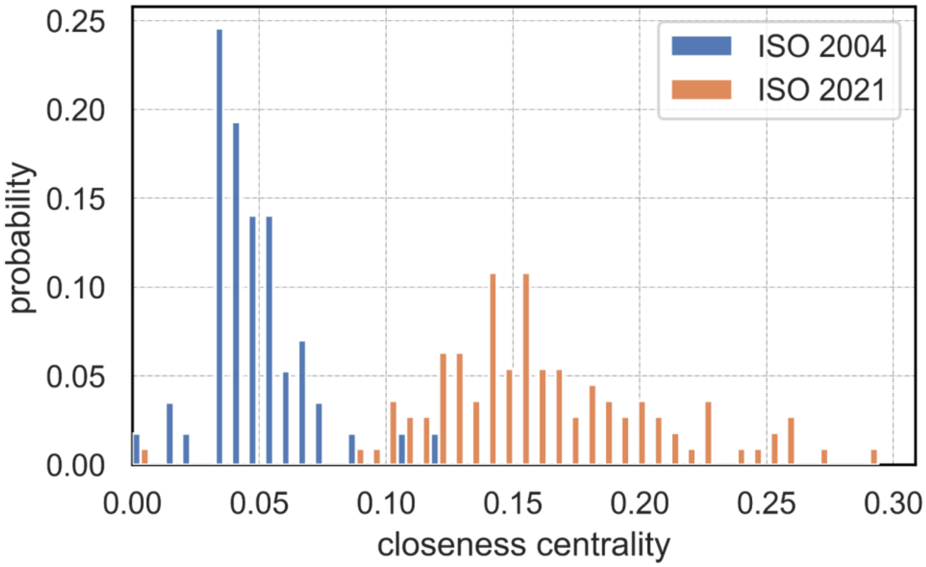


Figure 5.10 ISO 22156 complete networks closeness centrality
Means: ISO 22156:2004 = 0.047, ISO 22156:2021 = 0.161

Table 5.7 Closeness top nodes (scores) for ISO 22156:2004 and ISO 22156:2021

ISO 22156:2004 Implicit	ISO 22156:2004 Complete	ISO 22156:2021 Implicit	ISO 22156:2021 Complete
6.2.3 (0.0584)	6.2.3 (0.1193)	10.9.4 (0.0378)	6.2 (0.2940)
11.1.5 (0.0559)	6.2.2 (0.1091)	10.9.3 (0.0350)	6.4 (0.2711)
7.5 (0.0547)	15 (0.0862)	8.4.3 (0.0337)	5.3 (0.2602)
7.4 (0.0536)	16 (0.0737)	10.12.3 (0.0337)	14 (0.2586)
11.4 (0.0525)	7.4 (0.0729)	10.9.2 (0.0318)	10.2 (0.2554)

5.2.1.6 Centrality Summary

Utilizing the findings from Section 4.2.1, centrality metrics were used to investigate organizational issues in the ISO 22156 networks. Degree distribution, PageRank centrality, HITS centrality, betweenness centrality, and closeness centrality were explored. Centrality scores for ISO 22156:2004 and ISO 22156:2021 networks are visualized in Figure 5.11 and Figure 5.12, respectively.

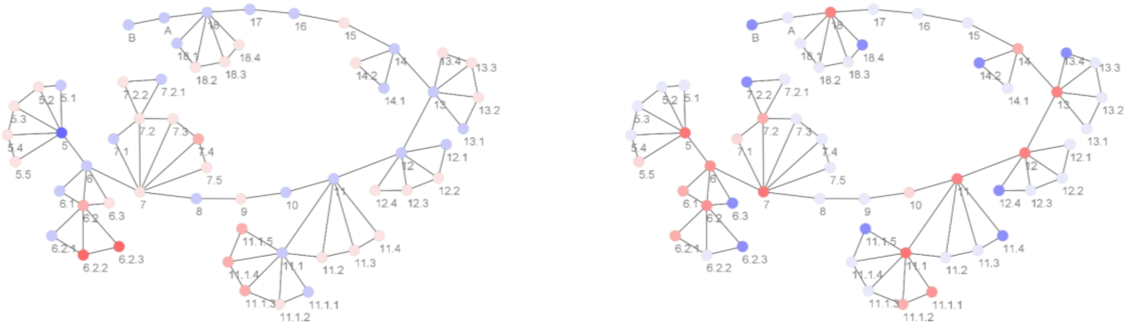
The degree distribution for ISO 22156:2004 and ISO 22156:2021 is not strongly log-normal and not considered to be scale-free. The total-degree distribution for ISO 22156:2021 displays a heavy tail with a positive skew, driven by outgoing references, which results in an increased mean degree. This may indicate decreased modularity and unclear provisional navigation functions.

PageRank identified provisions that are essential to design and would nearly always be used in a design instance, unlike the PageRank results for ACI 318. Equally, there are many commonly used provisions that are not found to be important by this metric.

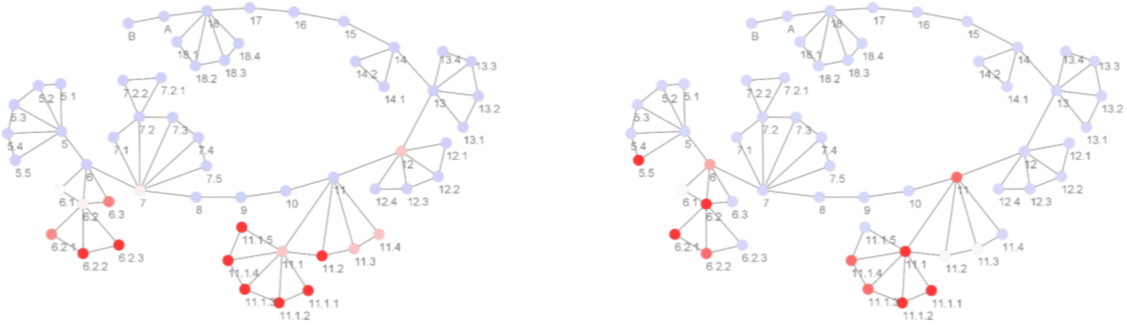
The HITS hub and authority centrality distributions do not give much information on the structure of the network, but clusters of nodes with high centrality in ISO 22156:2021 appear around Chapters 10 and 6, and Appendix D; all of which are new to the 2021 version – perhaps indicating a need for revision to improve the continuity of the standard.

Nodes with high betweenness scores represent provisions common to many design instances in ISO 22156:2021, which was consistent with betweenness results for ACI 318.

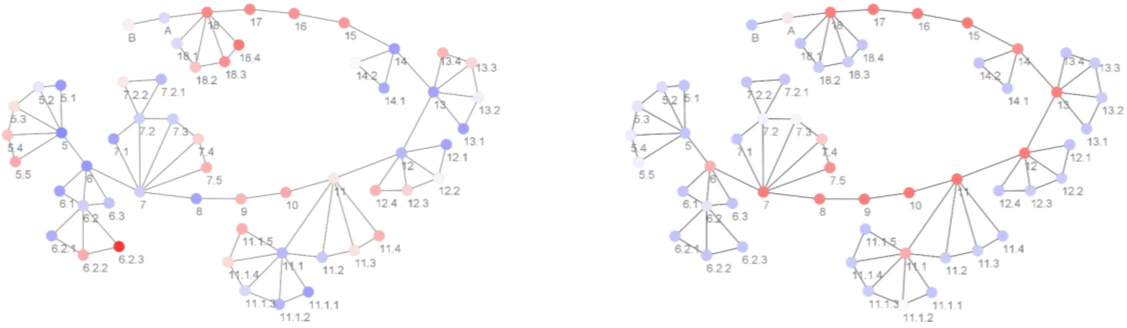
Closeness centrality distributions for ISO 22156:2021 indicates that the explicit edges play a significant role in the structure of the complete network. Closeness centrality scores for the ISO 22156:2021 complete network are representative of provisions users might find important for design.



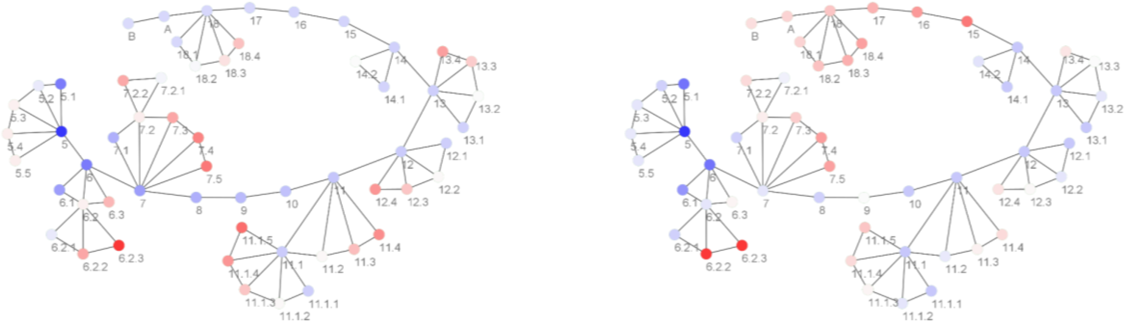
(a) in-degree **(b) out-degree**



(c) authority **(d) hub**



(e) PageRank **(f) betweenness**

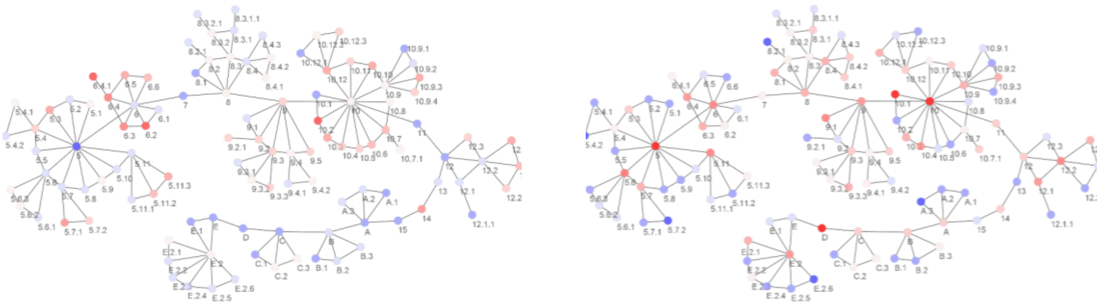


(g) closeness (implicit) **(h) closeness (complete)**

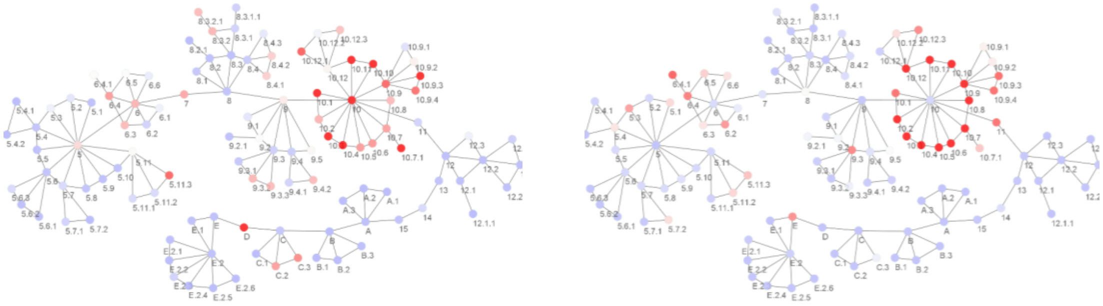
standard deviations from mean:

-2≤ -1 0 1 ≥2

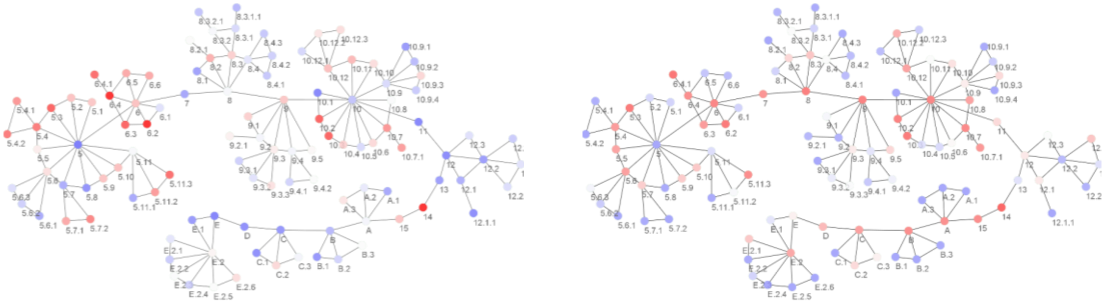
Figure 5.11 Summary of ISO 22156:2004 centralities. Explicit references are not shown. Where necessary, distributions were made normal-like using the Box-Cox transformation.



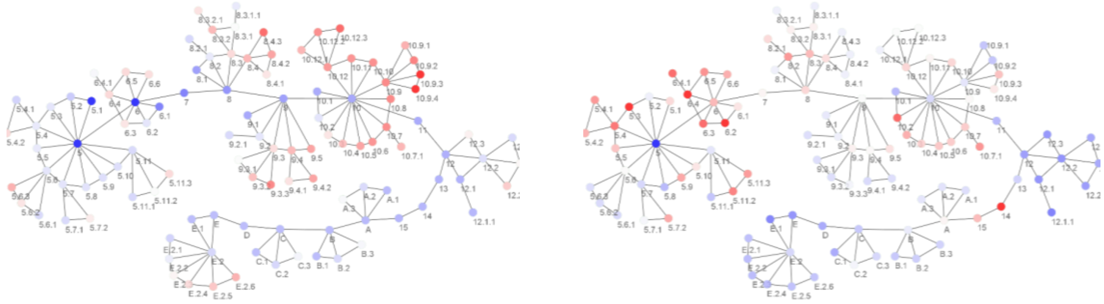
(a) in-degree (b) out-degree



(c) hub centrality (d) authority



(e) PageRank (f) betweenness



(g) closeness (implicit) (h) closeness (complete)

standard deviations from mean:

-2≤ -1 0 1 ≥2

Figure 5.12 Summary of ISO 22156:2021 centralities. Explicit references are not shown. Where necessary, distributions were made normal-like using the Box-Cox transformation.

5.2.2 Degree Assortativity

Table 5.8 reports the degree assortativity for the implicit and complete reference networks for both ISO 22156:2004 and ISO 22156:2021. Implicit networks appear to be slightly disassortative, while explicit references have a positive effect on network assortativity. All results show significant sensitivity to the jackknife test, likely because of the relatively small network sizes. In and out-degree assortativity were not investigated based on the lack of statistical significance observed in the analyses of the much larger ACI 318-11 and ACI 318-14 networks.

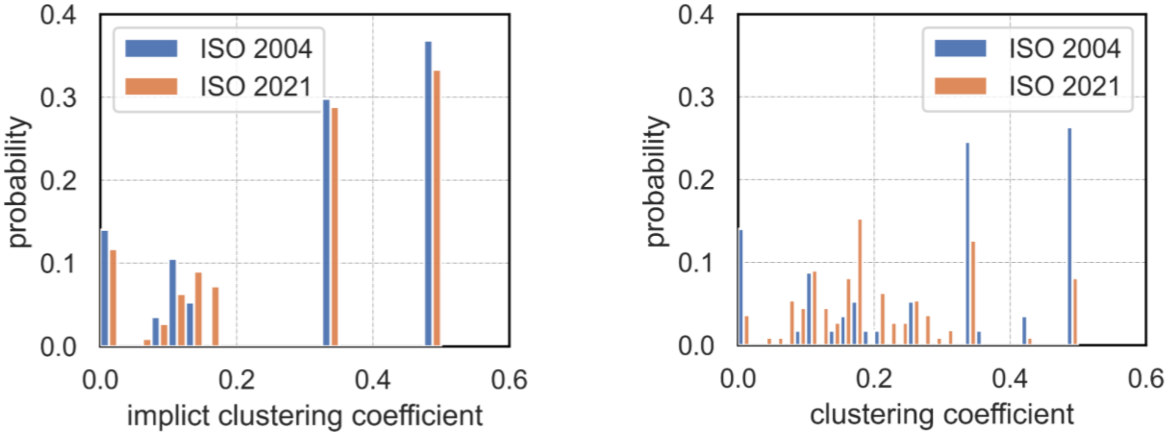
Table 5.8 ISO 22145 degree assortativity

Pearson correlation (jackknife error)

	ISO 22156:2004	ISO 22156:2021
Implicit	-0.221 (0.213)	-0.107 (0.097)
Complete	-0.050 (0.293)	0.179 (0.169)

5.2.3 Clustering and Motifs

The distributions for clustering coefficients in the complete reference networks of ISO 22156:2004 and ISO 22156:2021 are shown in Figure 5.13. Deviations from the mean are visualized for both standards' implicit and complete reference networks in Figure 5.14. Clustering trends are generally consistent with ACI 318 networks. Provisions with low clustering scores in ISO 22156:2021 are not preserved by explicit references, indicating disruption to the implicit hierarchy. Provisions deep in the implicit hierarchy are likely common sources and targets of explicit referencing.



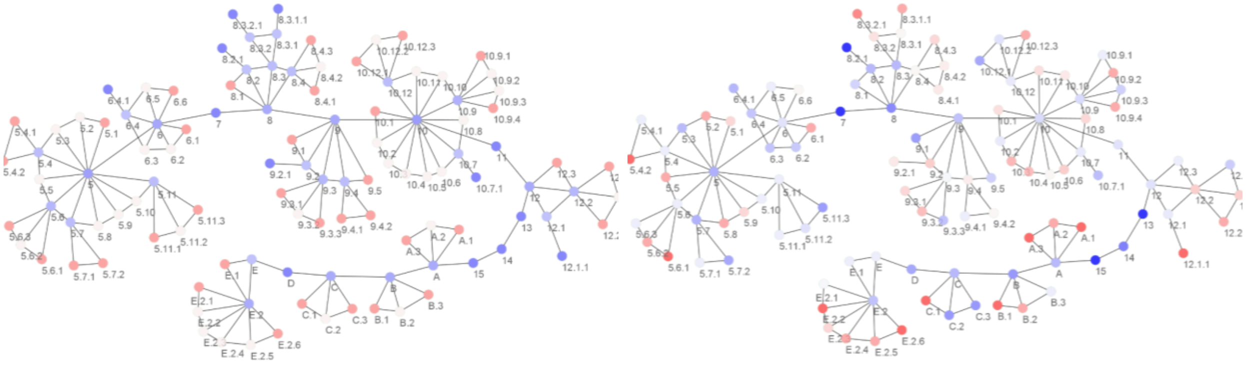
a) implicit network

b) complete network

Figure 5.13 Clustering coefficient distributions for ISO 22156:2004 and ISO 22156:2021 implicit (a) and complete (b) networks.

(a) ISO 22156:2004 implicit

(b) ISO 22156:2004 complete



(c) ISO 22156:2021 implicit

(d) ISO 22156:2021 complete

standard deviations from mean: -2≤ -1 0 1 ≥2

Figure 5.14 ISO 22156 clustering scoresfor implicit and complete networks.

Motif detection of subgraphs with 3, 4, and 5 nodes was performed for ISO 22156:2004 and ISO 22156:2021 implicit and complete networks using the process described in Section 4.2.3. A summary of results of the mFinder analysis is presented in Table 5.9 while complete statistics can be found in the supporting documentation. ID 38, the ‘feed-forward loop’, is the only 3-node motif found in all networks analyzed in this research and appears to be fundamental based on the implicit network definition adopted in Section 4.1. Similarly, 4-node motifs ID 78, 394, and 372 were found in all networks. Motif ID 108, the only additional 3-node motif found in the ISO 22156:2021 complete network indicates explicit references to the node previous in a hierarchical flow (i.e., back referencing). Shown in Figure 4.18, ID 108 is structurally similar to ID 38, except that both downstream nodes reference each other (instead of only one referencing another). Although motif criteria were not strictly met, the ISO 22156:2021 complete network shows more frequent occurrences of cyclic referencing structures (ID 98, 102, and 110) than expected based on synthetic networks. All other ISO 22156 networks investigated (Figure 5.15) slightly under express (with low confidence) motif ID 98. It is believed that identifying and reducing cyclic referencing structures could aid user-navigation and decouple provisions in the standard, allowing for continued (and expected) growth. Additionally, it is suspected that ID 108 may be detrimental to the user-experience by interrupting the implicit forward flow of the standard.

Table 5.9 Motifs found across ISO 22156:2004 and ISO 22156:2021

		ISO 22156:2004 Implicit	ISO 22156:2004 Complete	ISO 22156:2021 Implicit	ISO 22156:2021 Complete
sub-graph.	**3**	38	38	38	38, 108
	4	78, 394, 472	78, 394, 472	78, 344, 394, 472	16 motifs
	5	7 motifs*	7 motifs*	16 motifs	69 motifs
Criteria: z-score > 2, p-value<0.010, uniqueness >= 4, *not identical sets					

Table 5.10 ISO 22156:2004 and ISO 22156:2021 3-node subgraphs

	ID	Real Freq.	Synthetic Mean ± STD	z-score	p-value	Concentration (x 10^-3)
ISO 22156:2004 Implicit	6	62	86.9 ± 1.6	-15.64	1.000	364.71
	12	70	92.8 ± 2.6	-8.77	1.000	411.76
	14	0	0.0 ± 0.0		1.000	0.00
	36	0	24.3 ± 1.3	-18.28	1.000	0.00
	38	26	1.8 ± 1.3	18.53	0.000	152.94
	46	0	0.0 ± 0.0		1.000	0.00
	74	0	0.0 ± 0.0		1.000	0.00
	78	0	0.0 ± 0.0		1.000	0.00
	98	0	0.6 ± 0.8	-0.85	1.000	0.00
	102	0	0.0 ± 0.0		1.000	0.00
	108	0	0.0 ± 0.0		1.000	0.00
	110	0	0.0 ± 0.0		1.000	0.00
	238	0	0.0 ± 0.0		1.000	0.00
ISO 22156:2004 Complete	6	63	98.1 ± 2.0	-17.79	1.000	298.58
	12	82	114.5 ± 3.1	-10.53	1.000	388.63
	14	1	1.0 ± 0.1	0.12	0.985	4.74
	36	12	46.7 ± 1.8	-19.80	1.000	56.87
	38	38	3.5 ± 1.7	19.90	0.000	180.09
	46	0	0.0 ± 0.0		1.000	0.00
	74	1	1.0 ± 0.1	0.12	0.985	4.74
	78	0	0.0 ± 0.0		1.000	0.00
	98	0	0.8 ± 0.9	-0.97	1.000	0.00
	102	0	0.0 ± 0.1	-0.12	1.000	0.00
	108	0	0.0 ± 0.0		1.000	0.00
	110	0	0.0 ± 0.0		1.000	0.00
	238	0	0.0 ± 0.0		1.000	0.00
ISO 22156:2021 Implicit	6	163	218.0 ± 2.3	-23.83	1.000	386.26
	12	166	218.3 ± 3.3	-15.66	1.000	393.36
	14	0	0.0 ± 0.0		1.000	0.00
	36	0	53.8 ± 1.6	-32.72	1.000	0.00
	38	56	2.6 ± 1.6	33.56	0.000	132.70
	46	0	0.0 ± 0.0		1.000	0.00
	74	0	0.0 ± 0.0		1.000	0.00
	78	0	0.0 ± 0.0		1.000	0.00
	98	0	0.9 ± 0.9	-0.94	1.000	0.00
	102	0	0.0 ± 0.0		1.000	0.00
	108	0	0.0 ± 0.0		1.000	0.00
	110	0	0.0 ± 0.0		1.000	0.00
	238	0	0.0 ± 0.0		1.000	0.00
ISO 22156:2021 Complete	6	315	445.5 ± 4.8	-27.31	1.000	221.75
	12	526	654.3 ± 7.7	-16.77	1.000	370.29
	14	43	51.0 ± 2.0	-3.91	1.000	30.27
	36	267	387.8 ± 4.6	-26.34	1.000	187.96
	38	141	23.0 ± 4.5	26.25	0.000	99.26
	46	3	0.7 ± 0.8	2.91	0.027	2.11
	74	46	72.5 ± 2.7	-9.97	1.000	32.38
	78	1	1.9 ± 0.4	-2.23	0.991	0.70
	98	7	4.8 ± 2.1	1.06	0.205	4.93
	102	4	1.7 ± 1.3	1.78	0.085	2.82
	108	13	1.4 ± 1.2	9.75	0.000	9.15
	110	1	0.1 ± 0.4	2.24	0.140	0.70
	238	0	0.0 ± 0.0		1.000	0.00

IDs meeting motif criteria are shown in white in the table

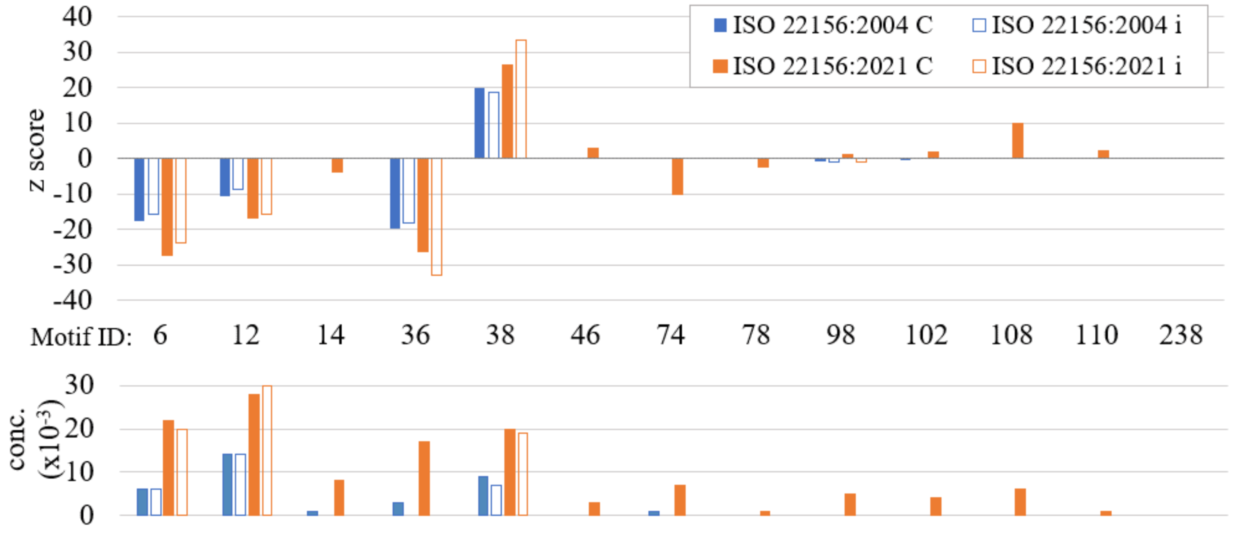


Figure 5.15 ISO 22156 motif z-scores and concentrations implicit (i) and complete (C) networks. Z-score indicates the magnitude of deviation from the subgraph concentration found in the real networks compared to the synthetic networks (n=1000).

5.2.4 Grouping Nodes by Connectivity

As described in Section 4.2.4, the Girvan-Newman algorithm is used to identify clusters within the standard based on connectivity. ISO 22156:2004 and ISO 22156:2021 maximized the network modularity scores (Eq. 4.8) at 6 clusters, which are respectively shown in Figure 5.16 and Figure 5.17. Cramer's V (Eq. 4.10) statistic for association between the clusters and provision parent chapters (reported in figure captions) show strong associations for each network. This is partly due to the small size of the networks and chapters (some of which are only one node) but also shows strong connectivity within chapters. In ISO 22156:2021 only provision 5.7.2, "Resistance to corrosion of metallic elements", is placed in a cluster without the rest of the provisions of its parent chapter, "Basic Requirements of Design". In the clustering analysis 5.7.2 is grouped (rather logically) with provisions of Chapter 10, "Joints and Splices", from which two provisions reference it explicitly. The limitations of association are evident in this analysis. Although Cramer’s V is a versatile association metric, by definition, it does not measure whether groups are exclusively associated with one another.

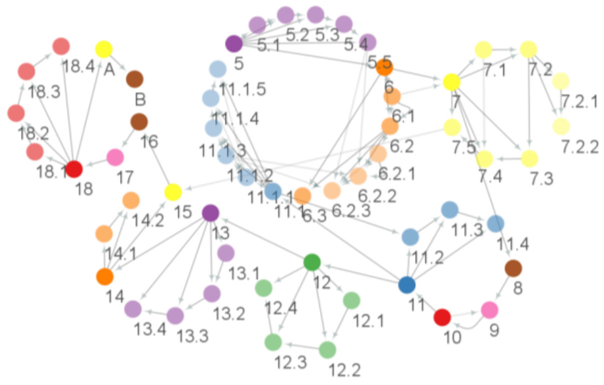


Figure 5.16 ISO 22156:2004 clustering by structure Clusters were found using the Girvan-Newman algorithm with edge betweenness as the decision feature. The Girvan-Newman modularity score is maximized at 6 clusters (0.619), each indicated by a ring of nodes. Colors in this plot match those representing chapters from Figure 5.1. Cramer's V against chapters = 0.952.

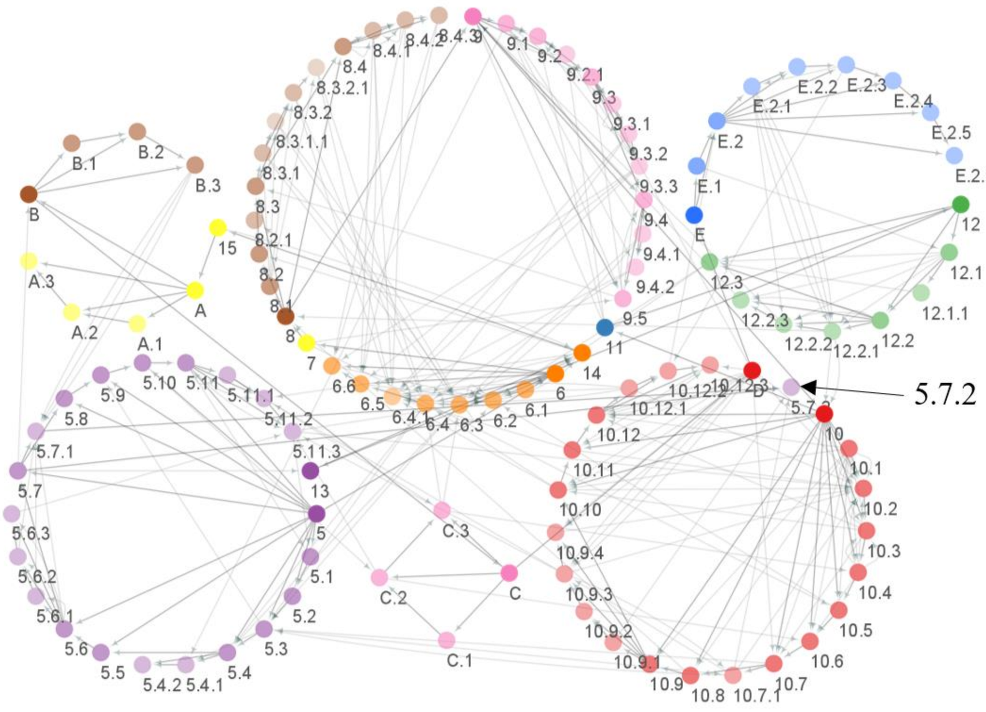


Figure 5.17 ISO 22156:2021 clustering by structure Clusters were found using the Girvan-Newman algorithm with edge betweenness as the decision feature. The Girvan-Newman modularity score is maximized at 6 clusters (0.727), each indicated by a ring of nodes. Colors in this plot match those representing chapters from Figure 5.2. Clause 5.7.2 is the lone provision seperated from its parent chapter. Cramer's V against chapters = 0.991.

5.2.5 Geodesic Paths

In the following sections heatmaps as described in Section 4.2.5 are presented in pairs (ISO 22156:2004 and ISO 22156:2021) based on the network type (implicit, explicit, and complete). These are followed by a plot showing the distribution of geodesic path lengths in the complete networks. In these heatmap matrices, each geodesic path between each pair of nodes is represented by a pixel where the vertical and horizontal 'axes' represent outgoing and incoming paths, respectively. Thus, the vertical axis datum is the 'source', and the horizontal axis datum is the 'target' of a path. Because the network is directed, the plots are not symmetric about the diagonal. In this analysis, "boilerplate" Chapters 1, 2, 3, and 4 were excluded and lettered chapters are ISO 22156 Appendices.

5.2.5.1 Implicit Networks

By inspection of the ISO 22156:2004 and ISO 22156:2021 implicit networks (Figure 5.18 and Figure 5.19, respectively) the significant changes made to the content of the standard in the revision are seen. Chapters in ISO 22156:2021 are apparently larger, based on the number of provisions represented by the size of the triangle above the diagonal, but are approximately of the same number.

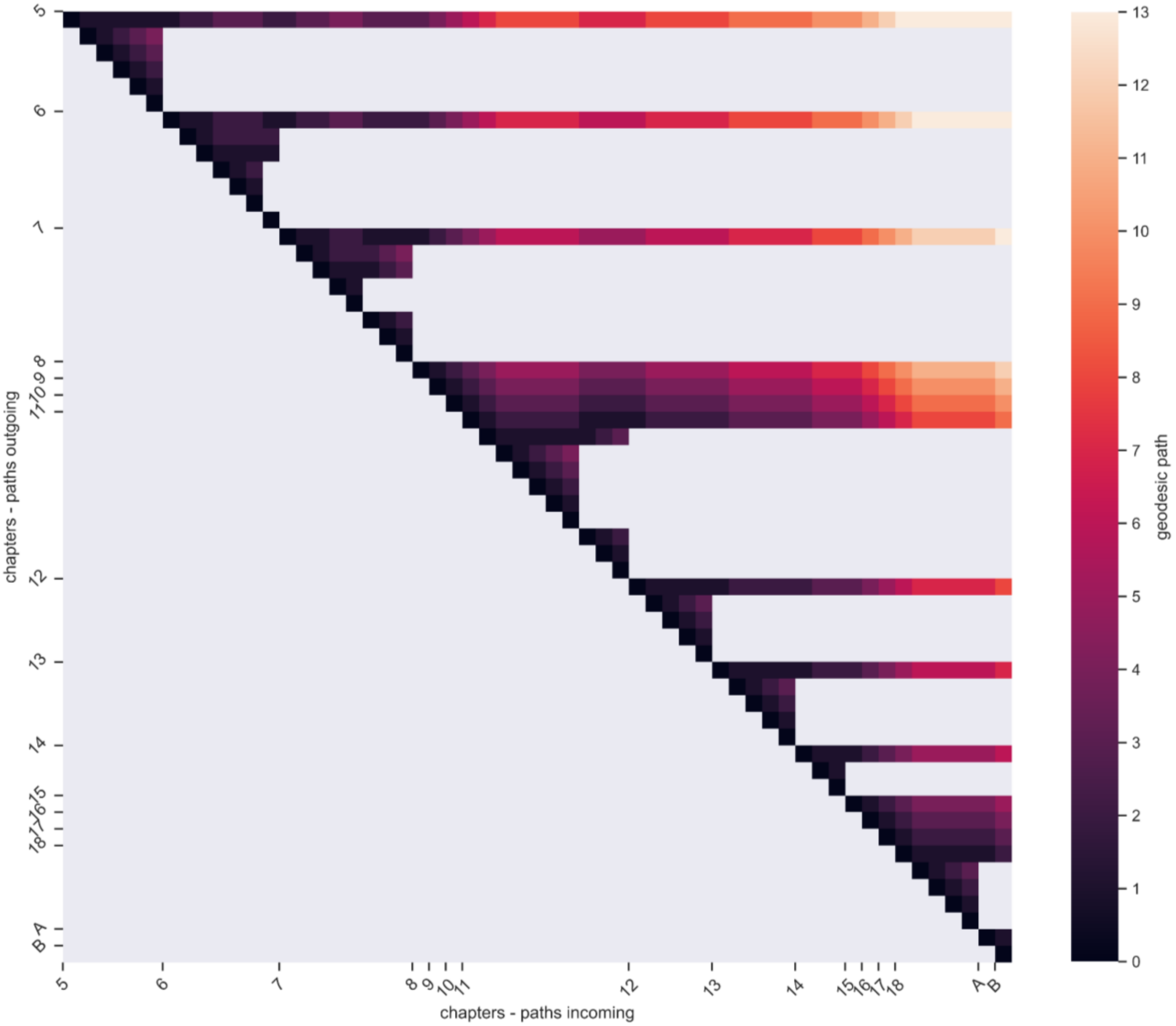


Figure 5.18 ISO 22156:2004 implicit network geodesic paths.

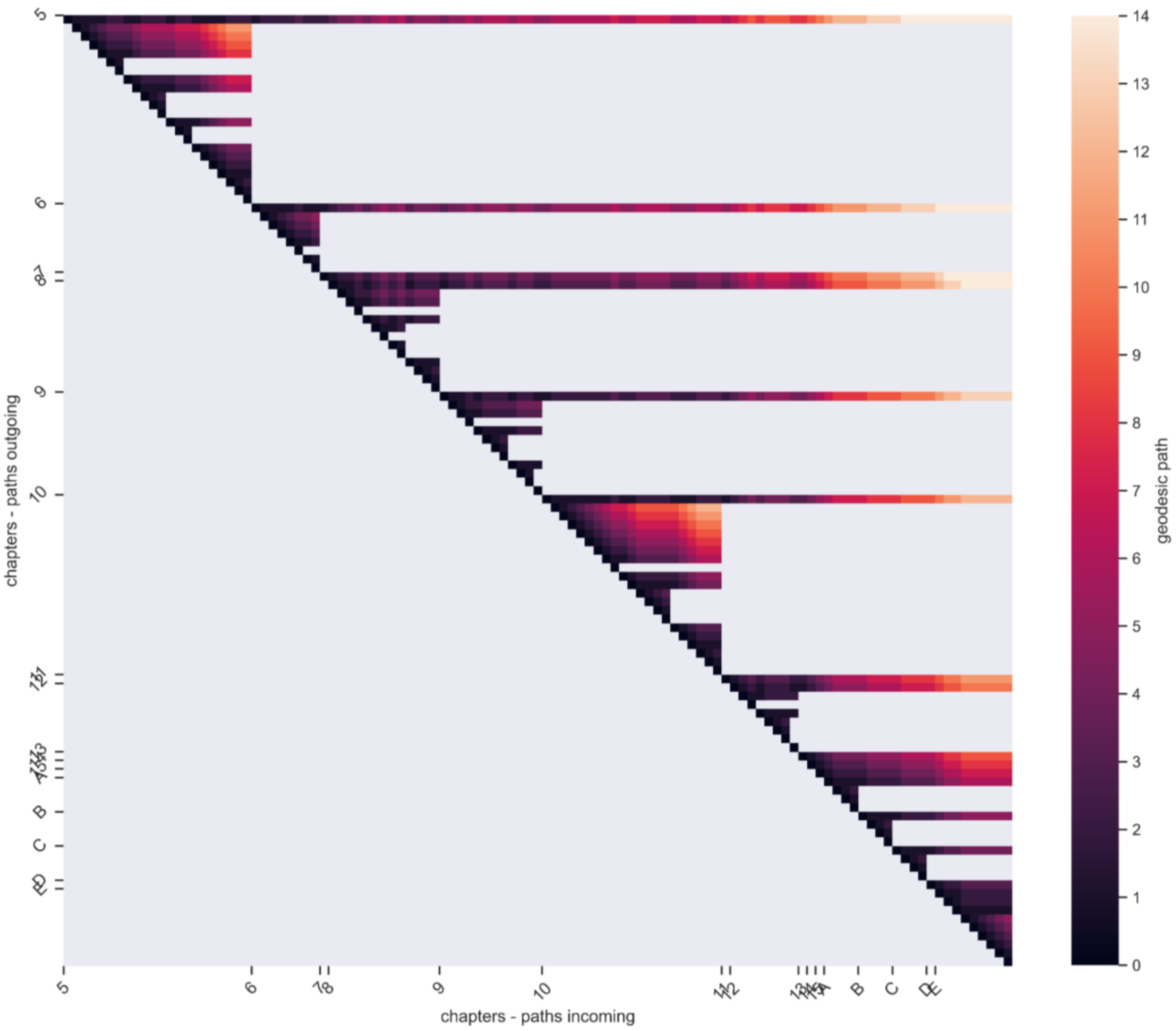


Figure 5.19 ISO 22156:2021 implicit network geodesic paths

5.2.5.2 Explicit Networks

Both ISO 22156:2004 (Figure 5.20) and ISO 22156:2021 (Figure 5.21) explicit networks display unique trends. ISO 22156:2004, likely due to its small size and limited content, has no explicit path length greater than one. That is, no provision is targeted from a source that itself was a target of an explicit reference. Meanwhile, the explicit network alone in ISO 22156:2021 has multiple paths of length 9, indicating a high degree of coupling between provisions. A greater proportion of explicit references (117 of 185 (63%)) in ISO 22156:2021 act backwards in the standard compared to ISO 22156:2004 (3 of 14 (21%)), ACI 318-11 (753 of 1354 (55%)), and ACI 318-14 (517 of 1197 (43%)).

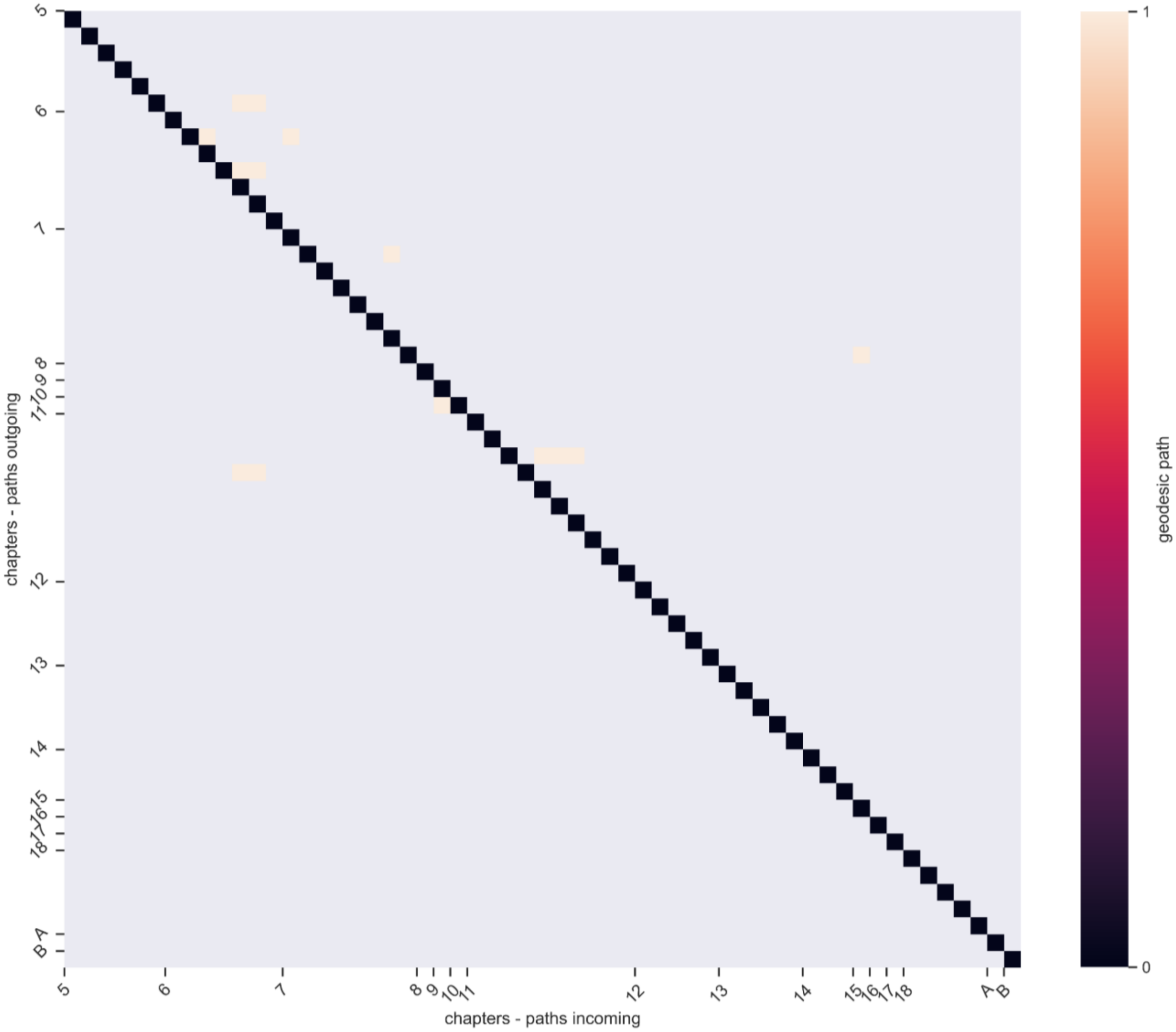


Figure 5.20 ISO 22156:2004 explicit network geodesic paths.

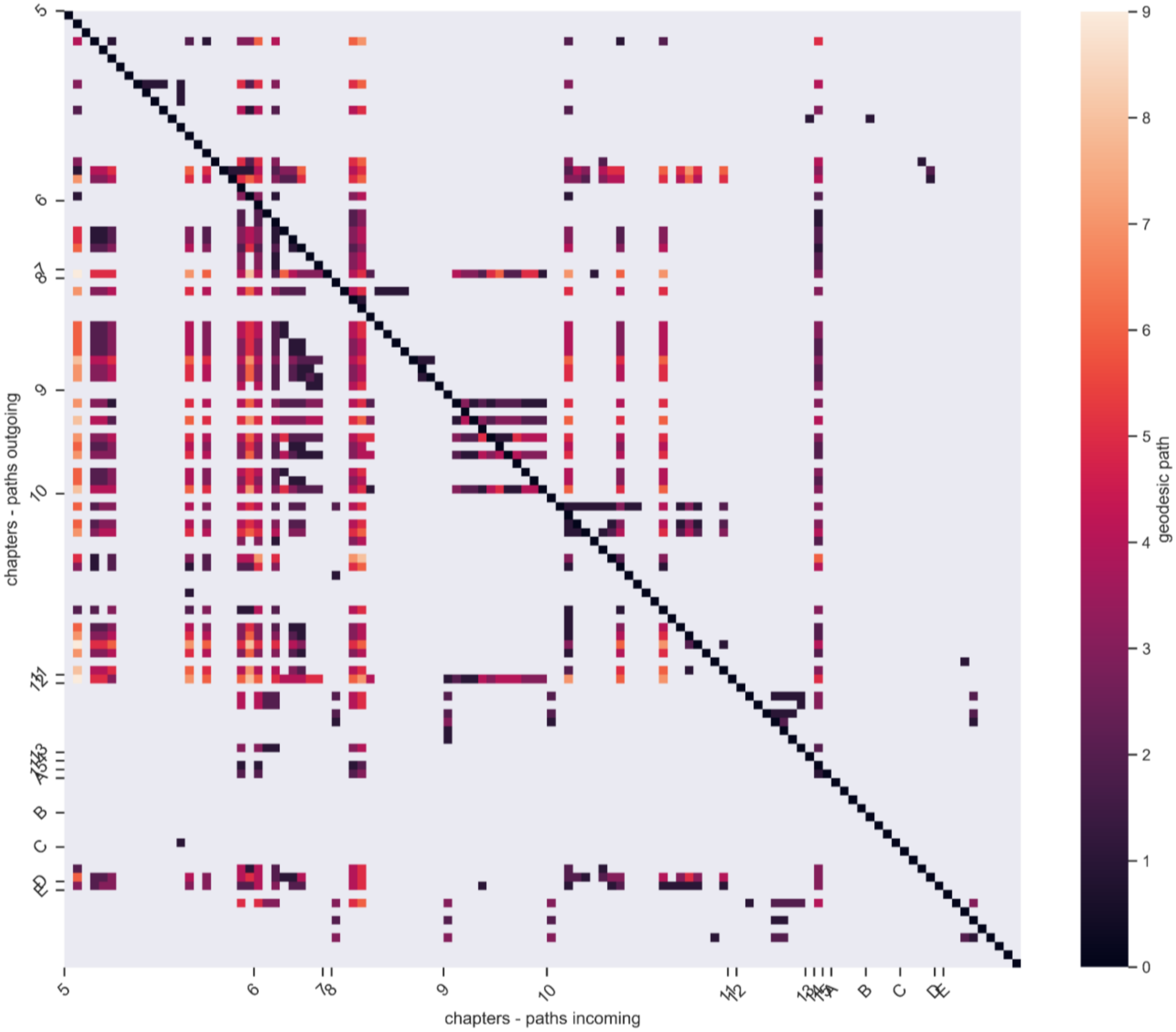
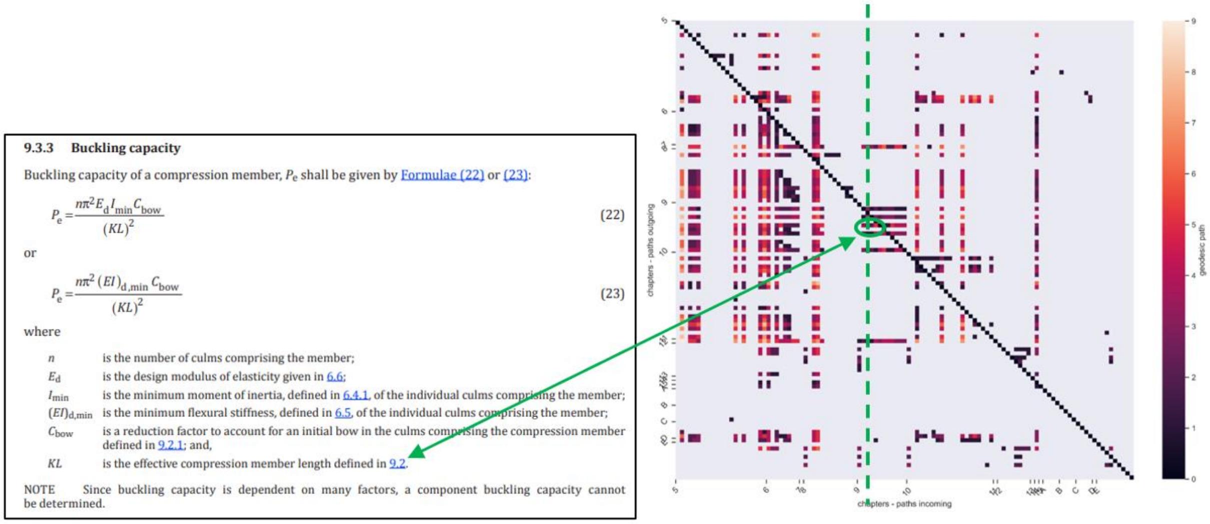


Figure 5.21 ISO 22156:2021 explicit network geodesic paths.

5.2.5.2.1 Example: Eliminating Back-References

A significant number of backward acting references in ISO 22156:2021 are associated with definitions of equation parameters. This is partially an artefact of required ISO format but also illustrates room for improvement for clarity. Areas of explicit referencing close to the diagonal are worth inspecting because they imply corrective action over the local implicit hierarchy. As an example, 9.3.3 "Buckling capacity", explicitly references 9.2 (and 9.2.1) for the definition of the effective length, *KL* (and C_{bow}). By following the vertical dotted line in the heatmap (Figure 5.22), it is evident that 9.2 is only referenced by 9.3 and Chapter 11 (which only sets $KL = 1$ for truss structures). This suggests that 9.2 would be more clearly presented as a subsection of 9.3.3.



9.3.3 Buckling capacity

Buckling capacity of a compression member, P_e shall be given by Formulae (22) or (23):

$$P_e = \frac{n\pi^2 E_d I_{min} C_{bow}}{(KL)^2} \tag{22}$$

or

$$P_e = \frac{n\pi^2 (EI)_{d,min} C_{bow}}{(KL)^2} \tag{23}$$

where

n	is the number of culms comprising the member;
E_d	is the design modulus of elasticity given in 6.6;
I_{min}	is the minimum moment of inertia, defined in 6.4.1, of the individual culms comprising the member;
$(EI)_{d,min}$	is the minimum flexural stiffness, defined in 6.5, of the individual culms comprising the member;
C_{bow}	is a reduction factor to account for an initial bow in the culms comprising the compression member defined in 9.2.1; and,
KL	is the effective compression member length defined in 9.2.

NOTE Since buckling capacity is dependent on many factors, a component buckling capacity cannot be determined.

Figure 5.22 Examining back-references identified in the ISO 22156:2021 heatmap.

5.2.5.3 Complete Networks

Because of the limited explicit references in ISO 22156:2004, the complete network (Figure 5.23) is similar to that of the implicit network (Figure 5.18). The combined effects of the implicit and explicit networks are most clearly visualized on this heatmap more than on any other due to its sparsity. Very little heat appears in the lower triangle, showing that this document largely progresses in the forward direction. The complete network of ISO 22156:2021 (Figure 5.24), on the other hand, is significantly impacted by the dense explicit network. Significant heat can be seen in the lower triangle, indicating a turbulent flow through the standard. The heat is concentrated around Chapter 6, “Member component and material properties”, which is essential to design and is referenced heavily in definitions for equations in later chapters. Chapter 6, in this manner, may be considered to be a “toolbox” chapter, using the ACI 318 parlance.

Some horizonal banding is apparent (similar to that of Figure 4.27) but is limited to only two chapters (not including appendices). This indicates that the deepest part of the implicit hierarchy is referencing out to other provisions. This could be a symptom of poor structure but could also be a ‘growing pain’ of the standard. ISO 22156:2021 is technically dense, yet not mature enough to cover all design cases, particularly with respect to detailing requirements. It is plausible then, that as the standard evolves to cover more details, implicit hierarchies become deeper and less dependent, generating horizontal banding in the complete network geodesic heatmap. The format constraints imposed by ISO when revising a document may also contribute to the apparently poor structure, especially when the content has been revised as significantly as is the case in ISO 22156:2021.

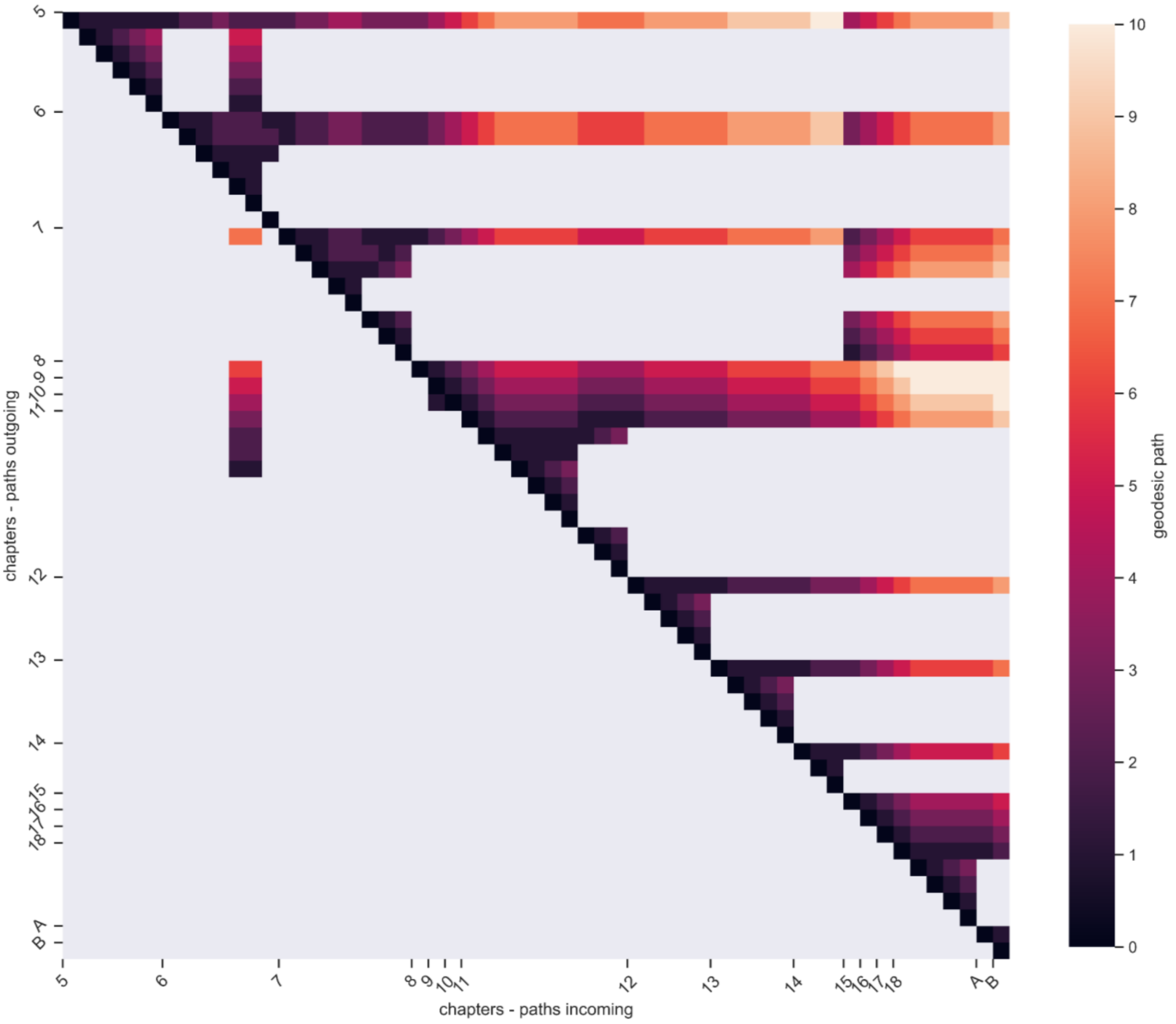


Figure 5.23 ISO 22156:2004 complete network all pairs geodesic paths.

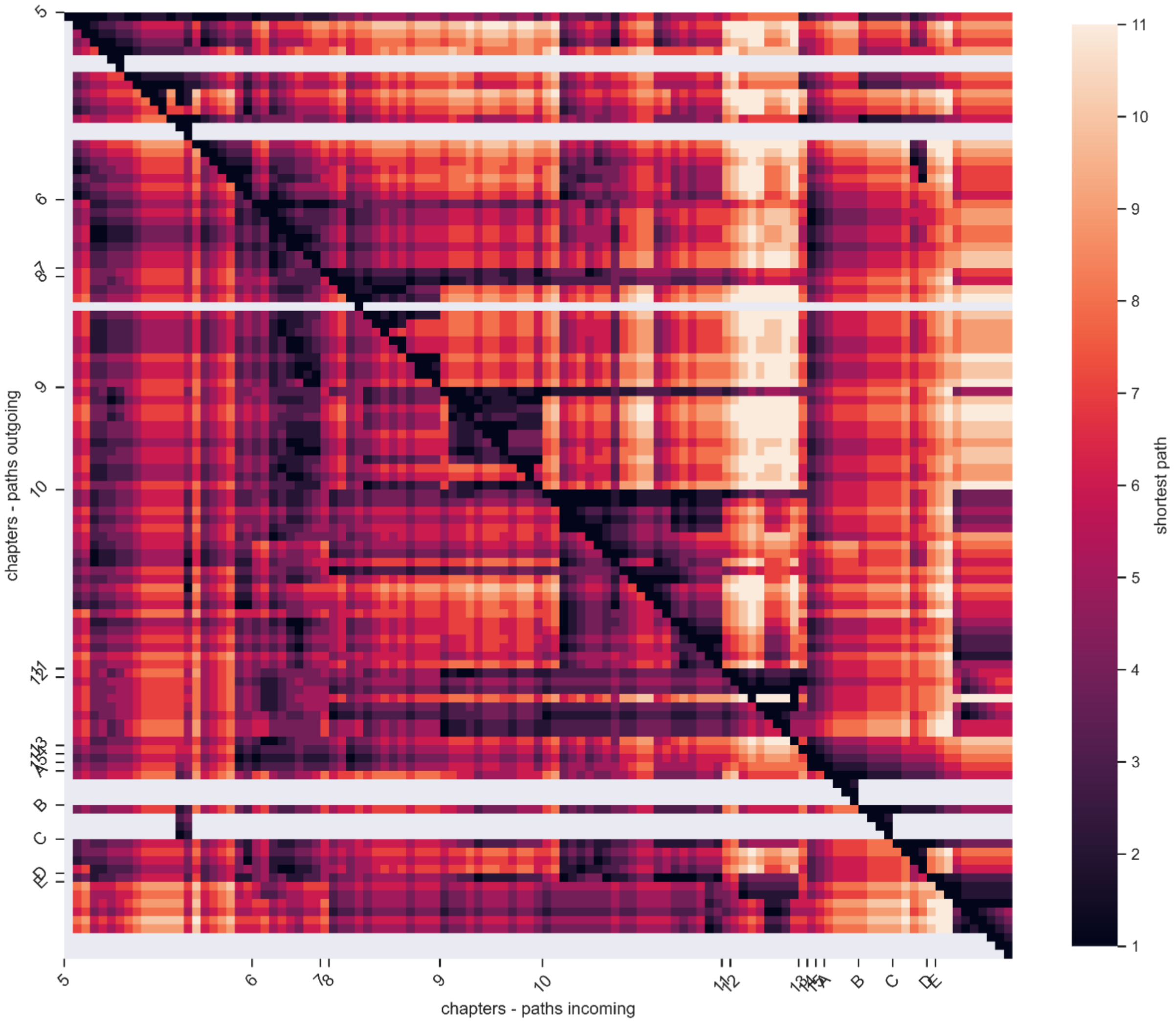


Figure 5.24 ISO 22156:2021 complete network all pairs geodesic paths. Heat in the lower triangle indicates ‘backwards’ referencing and is most concentrated in Chapter 6.

5.2.5.3.1 Path Distributions

The distributions of geodesic path lengths between all pairs of nodes in the complete ISO 22156:2004 and ISO 22156:2021 networks are presented in Figure 5.25 and Figure 5.26, respectively. The cumulative curves were tested for best fit against common distributions and found to be well represented by a normal distribution in both cases. The distributions for both ISO 22156:2004 (skewness = 0.39) and ISO 22156:2021 (skewness = 0.15) demonstrate a slightly positive skew.

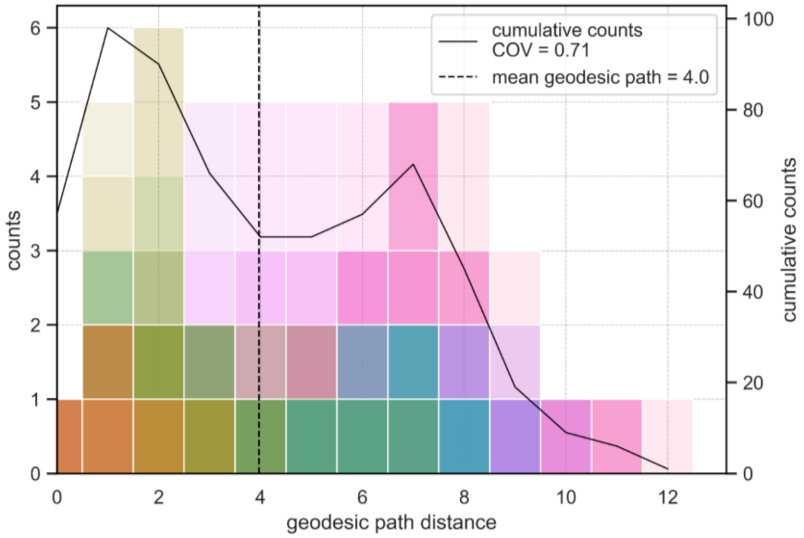


Figure 5.25 ISO 22156:2004 complete geodesic paths distribution. The essentially normal cumulative distribution is indicated by the black line (kurtosis = 2.11 , skewness = 0.39).

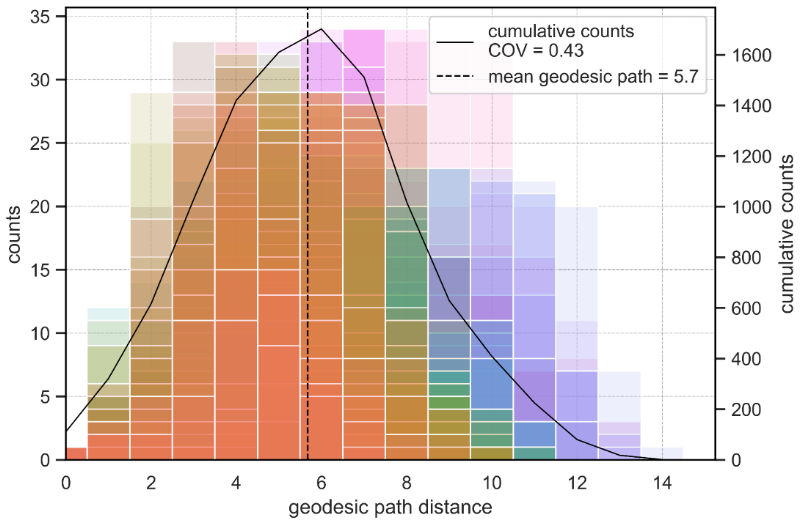


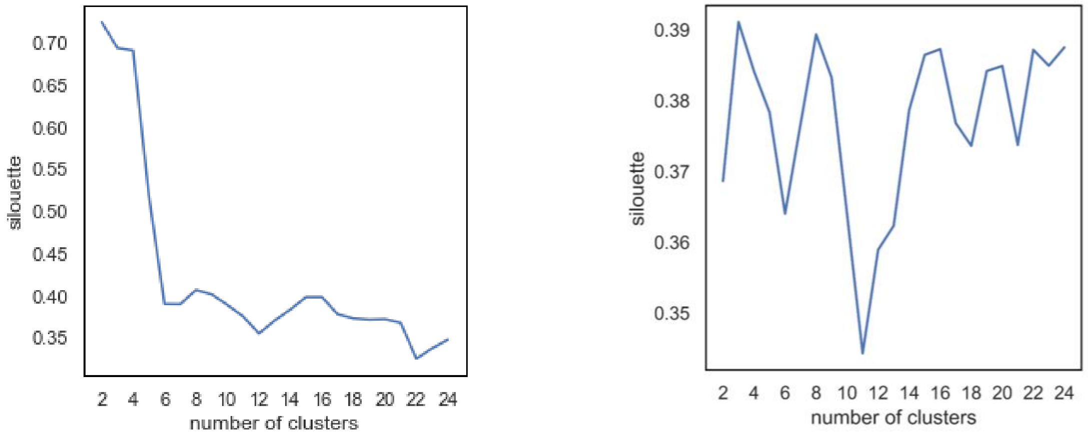
Figure 5.26 ISO 22156:2021 complete geodesic paths distribution. The essentially normal cumulative distribution is indicated by the black line (kurtosis = 2.73 , skewness = 0.15).

5.3 Semantic Representations of Provisions

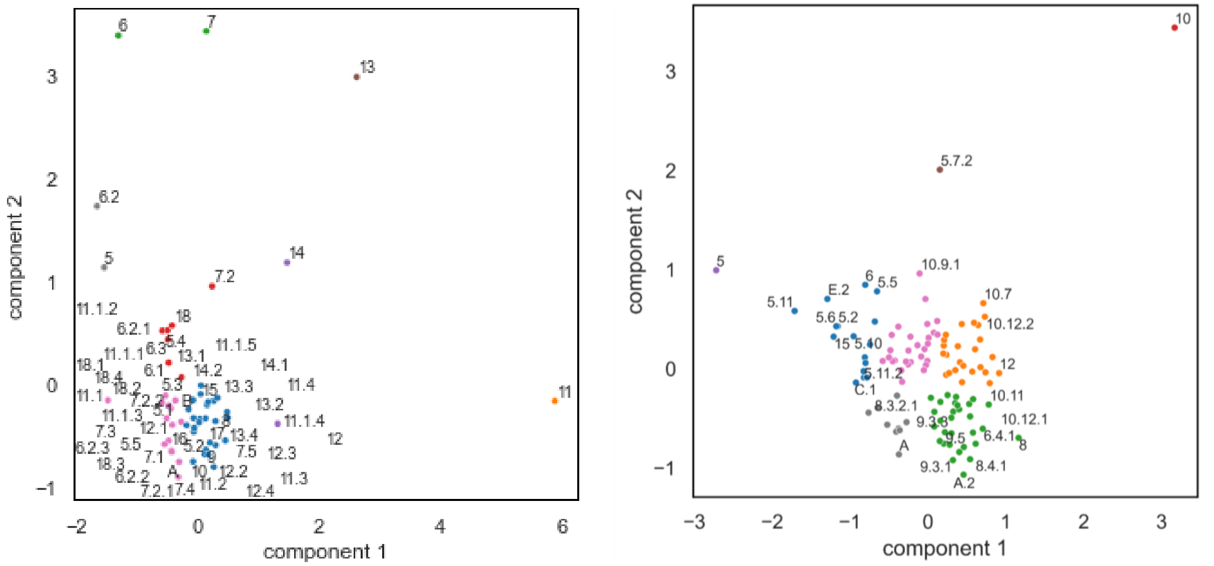
Although results from Section 4.3 were not particularly compelling or insightful with respect to understanding navigational complexity, a similar line of inquiry is pursued here for completeness. First, provisions are clustered by k-means using vector embeddings. These clusters are tested for association with the structural clusters identified in Section 5.2.4, as well those defined by the document chapters. Then, similarity between provision embeddings is mapped for all provision pairs, again utilizing both GPT3 and spaCy embeddings. Finally, the correlations between geodesic path length and similarity score for node pairs are plotted for both standards with both embedding representations.

5.3.1 Clustering Provisions by Embedding

The clustering workflow described in Section 4.3.1 for ACI 318 was followed for ISO 22156. Silhouette analysis for ISO 22156:2004 identified between 4-8 clusters (Figure 5.27a) and was inconclusive for ISO 22156:2021 (Figure 5.27b), but not highly variable using spaCy embeddings. Silhouette analysis for GPT3 shows similar results (Figure 5.28). Girvan-Newman modularity analysis (Section 5.2.4) identified 6 clusters as structurally optimal for each. Here, 8 clusters are identified as appropriate and is a local maximum in each silhouette analysis for ISO 22156. Clusters in the spaCy and GPT3 embedding space are shown in Figure 5.27(c, d) and Figure 5.28(c, d), respectively. Zero-vectors were removed from sentence embeddings before averaging. Figure 5.27(c, d) shows a slight shift toward the origin from the 2004 to the 2021 version, likely due to the increased length of provisions. Notably, the GPT3 embeddings for ISO 22156:2021 tended to cluster chapter titles together (Figure 5.28d, right side of plot), possibly due to the provision length or syntactic qualities (i.e., titles are typically noun phrases).

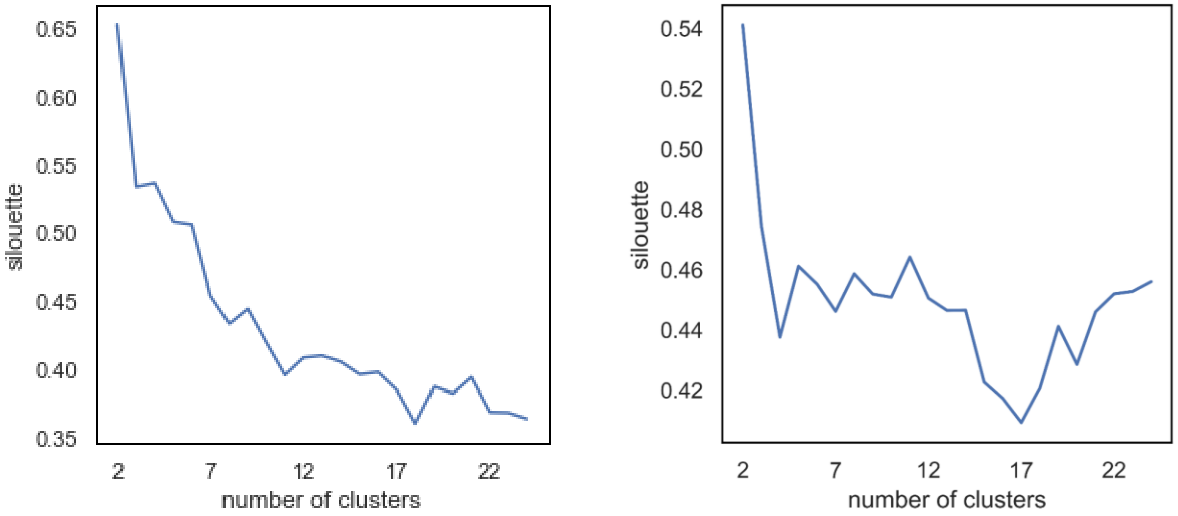


(a) ISO 22156:2004 **(b) ISO 22156:2021**

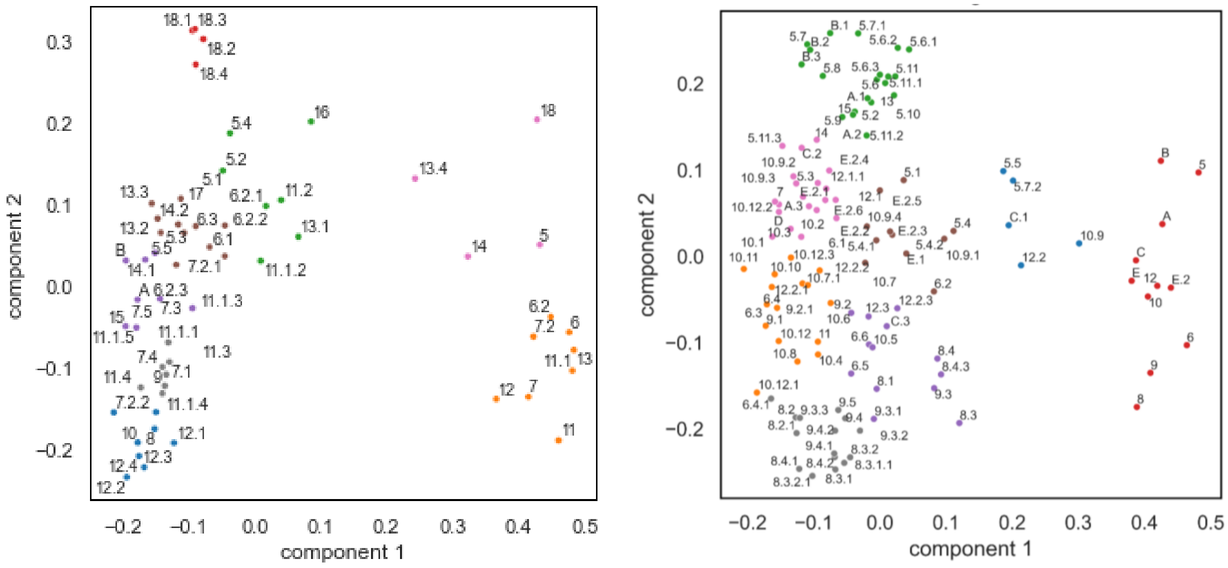


(c) ISO 22156:2004 **(d) ISO 22156:2021**

Figure 5.27 ISO 22156 spaCy clustering silhouette analysis (a, b) and clusters (c, d) visualized using PCA. Cluster colors are only for visualization, some neighboring clusters share colors.



(a) ISO 22156:2004 **(b) ISO 22156:2021**



(c) ISO 22156:2004 **(d) ISO 22156:2021**

Figure 5.28 ISO 22156 GPT3 clustering silhouette analysis (a, b) and clusters (c, d) visualized using PCA. Cluster colors are only for visualization, some neighboring clusters share colors.

For some measure of the meanings of the clusters, Table 5.11 presents the terms closest to the centroids of each cluster in the spaCy embedding space. Many of the terms clustered near centroids might be expected to be represented by a chapter or section in ISO 22156, particularly those of ISO 22156:2004. Centroid terms in ISO 22156:2021 appear less representative of the text (notice prevalence of ‘thus’, ‘necessary’, etc.), possibly due to larger provisions and larger clusters (about twice the size), both of which are averaged and can reduce meaningful features in this analysis. Table 5.12 presents a slightly different analysis for the ISO 22156 GPT3 embedding space. By inspection, many of the five nearest neighbors are from the same chapter or sections in the standard. However, some in ISO 22156:2021 appear to be of chapter titles (clusters 2 and 6), possibly indicating the syntactic influence of the text on the embeddings. Statistical association between these groups is discussed in the next section.

Table 5.11 ISO 22156 spaCy embeddings cluster centroids.
Unique terms from 10 nearest to k-means cluster centroids are shown each standard.

Cluster	ISO 22156:2004	ISO 22156:2021
0	{'necessary', 'therefore', 'appropriate'}	{'necessary', 'particular', 'appropriate'}
1	{'joint', 'joints', 'tendons'}	{'maximum', 'thus', 'i.e.'}
2	{'panel', 'paneling', 'panels'}	{'welds', 'splices', 'joints'}
3	{'concept', 'design', 'concepts'}	{'surface', 'structure', 'i.e.'}
4	{'requirement', 'requirements', 'basic'}	{'design', 'requirements', 'basic'}
5	{'soil', 'concrete', 'reinforcement'}	{'component', 'materials', 'components'}
6	{'materials', 'material', 'properties'}	{'necessary', 'thus', 'i.e.'}
7	{'general', 'certain', 'terms'}	{'necessary', 'appropriate', 'i.e.'}

Table 5.12 ISO 22156 GPT3 embeddings cluster centroids.
5 nearest neighbors to k-means cluster centroids are shown for each standard.

Cluster	ISO 22156:2004	ISO 22156:2021
0	7, 11.1 , 7.2 , 6 , 6.2	5.4, 5.1 , 5.5 , 8.4.3 , 8.4
1	11.1.1 , 11.1.4 , 11.1.5 , 12.3 , 12.2	5.7.1 , 5.7 , 5.6 , 5.11.1 , 5.2
2	5.1 , 5.3 , 5.4 , 5.2 , 6.3	10.9 , 10 , 9 , 8 , 6
3	7.3 , 7.4 , 7.2.2 , 7.1 , 7.5	10.1 , 10.3 , 10.2 , 10.9.2 , 10.11
4	18.2 , 18.3 , 18.1 , 18.4 , 5.4	6.3 , 6.4 , 6.5 , 6.6 , 10.4
5	11.1.2 , 6.2.1 , 6.1 , 11.2 , 16	12.1.1 , 12.1 , 12.2.2 , E.2.6 , E.2.4
6	14.1 , 14.2 , 13.2 , 13.3 , 17	B , A , C , E , 5
7	B , A , 5.5 , 7.5 , 7.2.2	8.3.1 , 9.4.2 , 8.3.2 , 8.3.1.1 , 8.3.2.1

5.3.1.1 Association Between Semantic and Structural Clusters

The association between clusters identified through the various methods presented here can be investigated utilizing Cramer's V statistic (Section 4.2.4). Table 5.13 and Table 5.14 show the symmetric association matrices for ISO 22156:2004 and ISO 22145:2021 clusters. Results are similar across both versions and similar to those of ACI 318 presented in Section 5.3.1.1; a) structural clustering (GN 6, Section 5.2.4) has the greatest association with chapters, b) GPT3 clusters are well associated with chapters, c) GPT3 clusters have the highest average association with other clustering methods, and d) spaCy clusters have poor to moderate associations in all cases. Associations between spaCy embeddings and other clustering results are greater in ISO 22156:2021 than in ISO 22156:2004, for reasons that are unclear.

Table 5.13 ISO 22156:2004 cluster association matrix

	Chapter	**GN 6**	**spaCy**	**GPT3**
Chapter	1	0.952	0.399	0.749
GN 6	0.952	1	0.335	0.636
spaCy	0.399	0.335	1	0.335
GPT3	0.749	0.636	0.335	1

Table 5.14 ISO 22156:2021 cluster association matrix

	Chapter	**GN 6**	**spaCy**	**GPT3**
Chapter	1	0.991	0.458	0.657
GN 6	0.991	1	0.497	0.653
spaCy	0.458	0.497	1	0.554
GPT3	0.657	0.653	0.554	1

5.3.2 Semantic Similarity Between Provisions

Similarity analysis was conducted between all pairs of provisions in ISO 22156:2004 and ISO 22156:2021 using both spaCy and GPT3 embeddings. Although there appears to be higher degrees of similarity between Chapters 7 through 13, it's clear in Figure 5.29 that spaCy embeddings can distinguish chapter titles from other provisions, but not much else in ISO 22156:2004. Relationships between titles and other provisions likely account for the smaller 'hump' in the distribution of similarity scores shown in Figure 5.30. GPT3 results for ISO 22156:2004 (Figure 5.31) show a similar trend to that of the spaCy embeddings, but with greater inter-chapter similarities visible in most chapters. Figure 5.32 show two 'humps' in the distribution, much like those of Figure 5.30, likely with the same explanation.

Results for ISO 22156:2021 follow similar trends as those found in ISO 22156:2004, and ACI 318. spaCy embeddings can usually differentiate between titles and provisions with more text and sometimes the inter-chapter relationships are apparently stronger than intra-chapter relationships (Figure 5.34). Figure 5.34 shows the title vs other provision hump in the spaCy ISO 22156:2021 distribution is not as pronounced as in other analyses in this research. Similarity between GPT3 embeddings (Figure 5.35) shows clear differentiation between titles and typical provisions and inter-chapter similarities are clearly stronger than intra-chapter similarities, particularly in middle portion of the standard. This indicates that GPT3 could be useful in classifying provisions by topic in ISO 22156:2021. The similarity score distribution for ISO 22156:2021 GPT3 (Figure 5.36) is typical given the previous analysis.

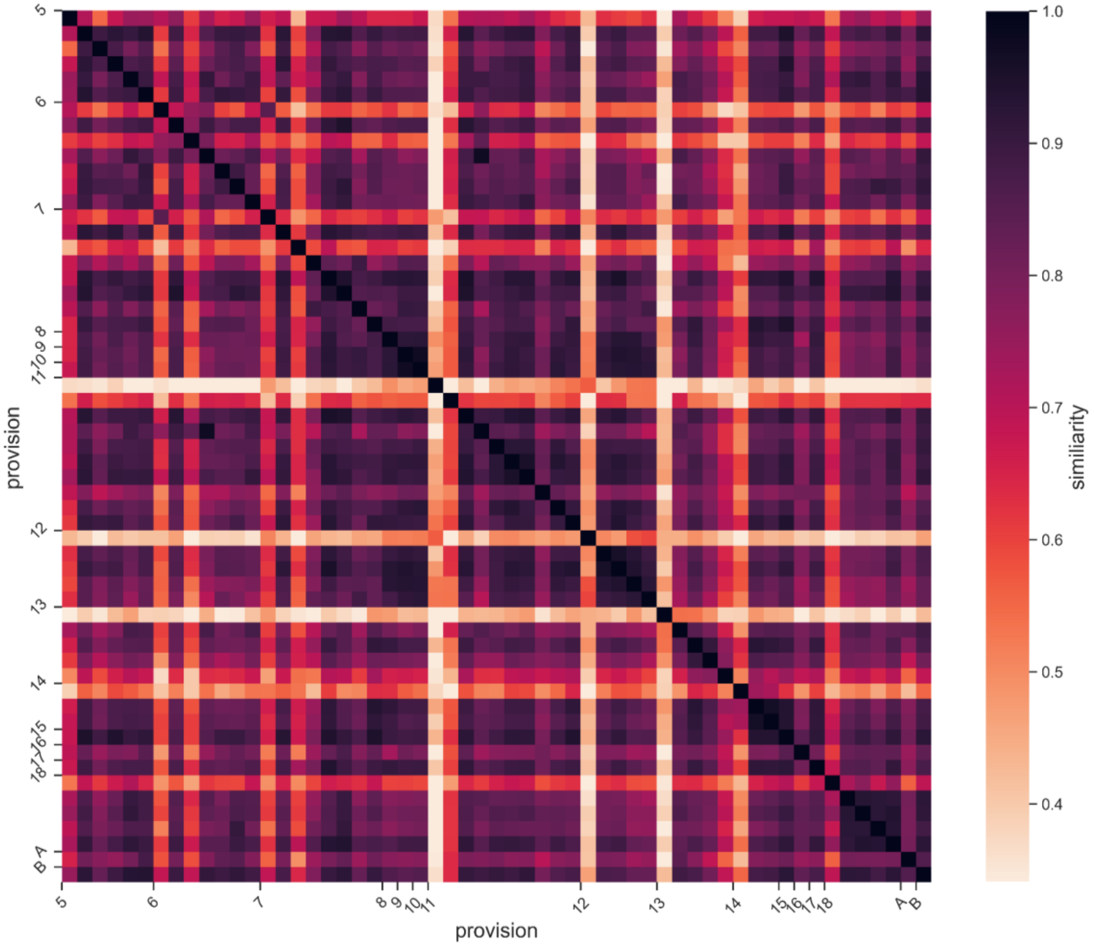


Figure 5.29 ISO 22156:2004 spaCy similarity between all provisions.

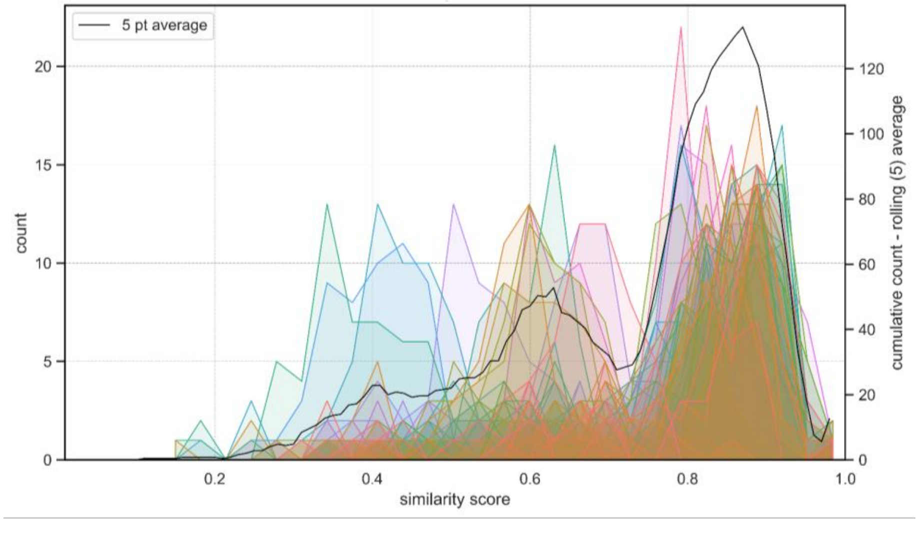


Figure 5.30 ISO 22156:2004 spaCy similarity score distribution.

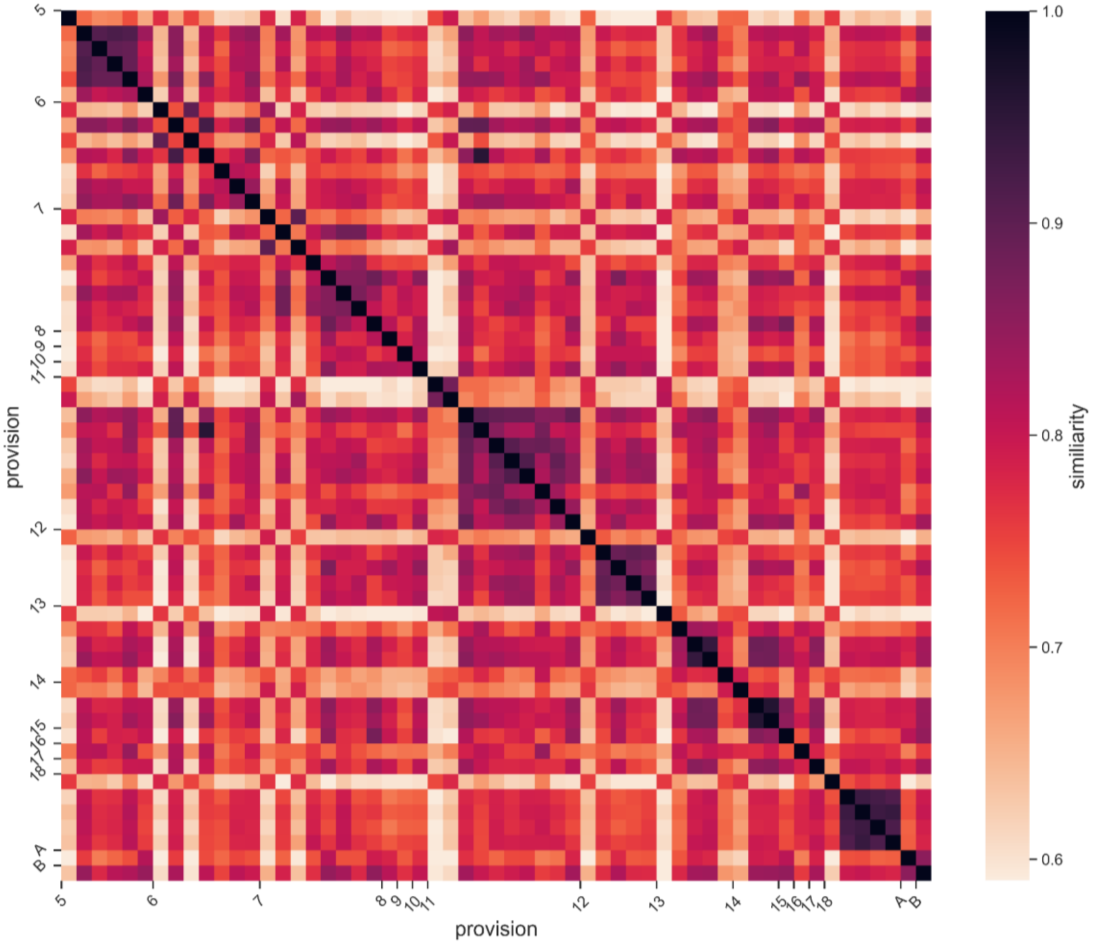


Figure 5.31 ISO 22156:2004 GPT3 similarity between all provisions.

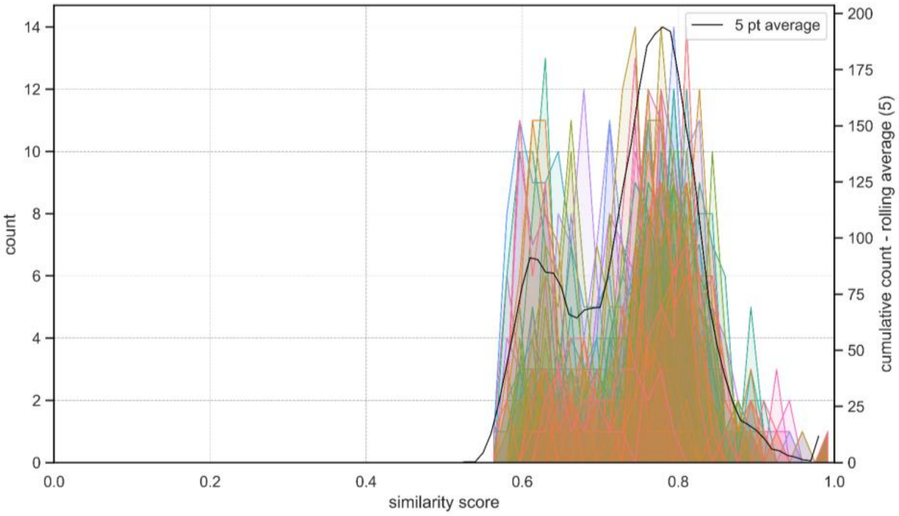


Figure 5.32 ISO 22156:2004 GPT3 similarity score distribution.

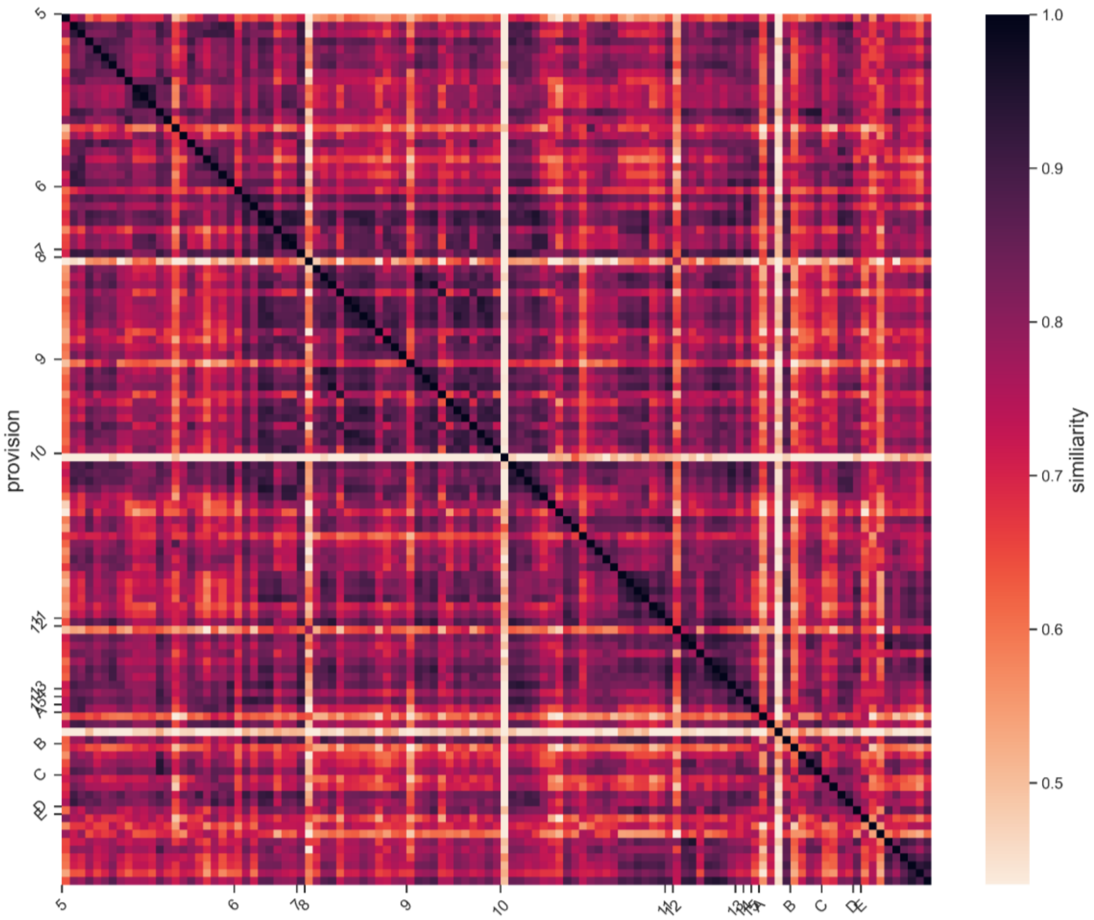


Figure 5.33 ISO 22156:2021 spaCy similarity between all provisions.

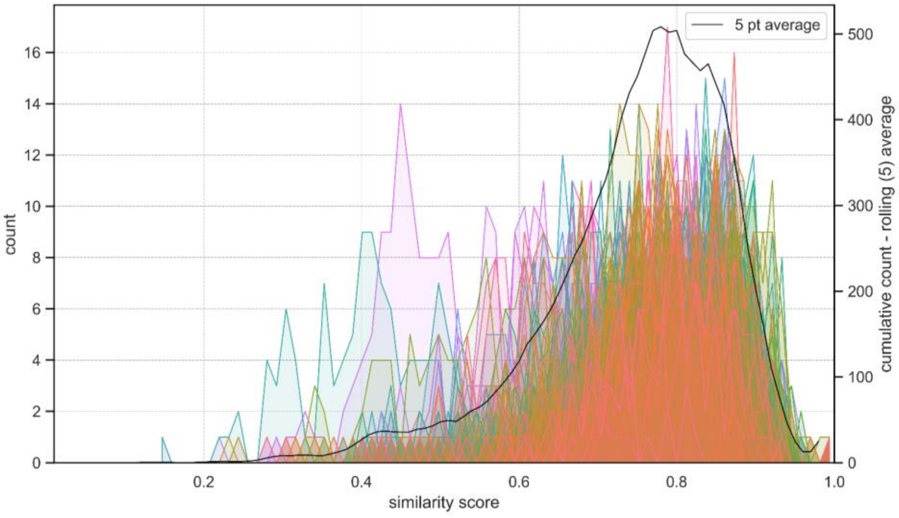


Figure 5.34 ISO 22156:2021 spaCy similarity score distribution.

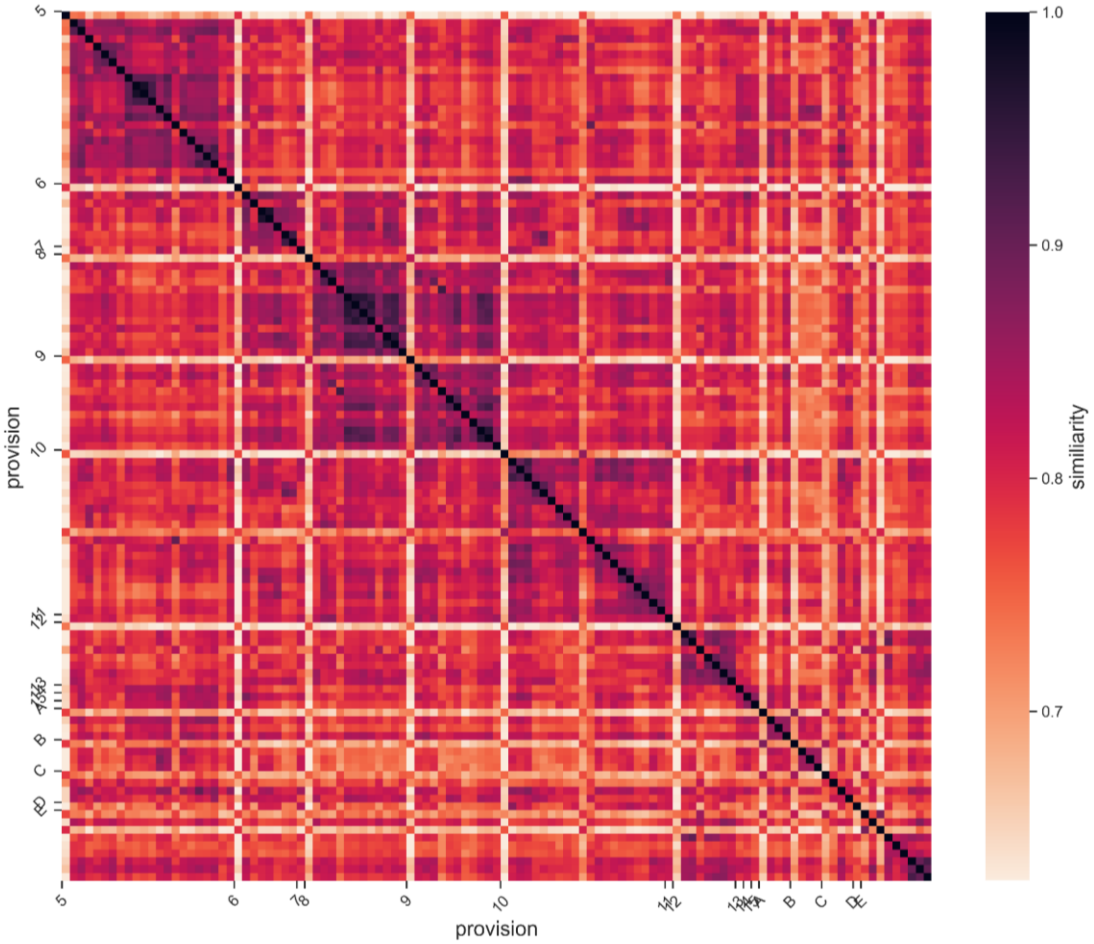


Figure 5.35 ISO 22156:2021 GPT3 similarity between all provisions.

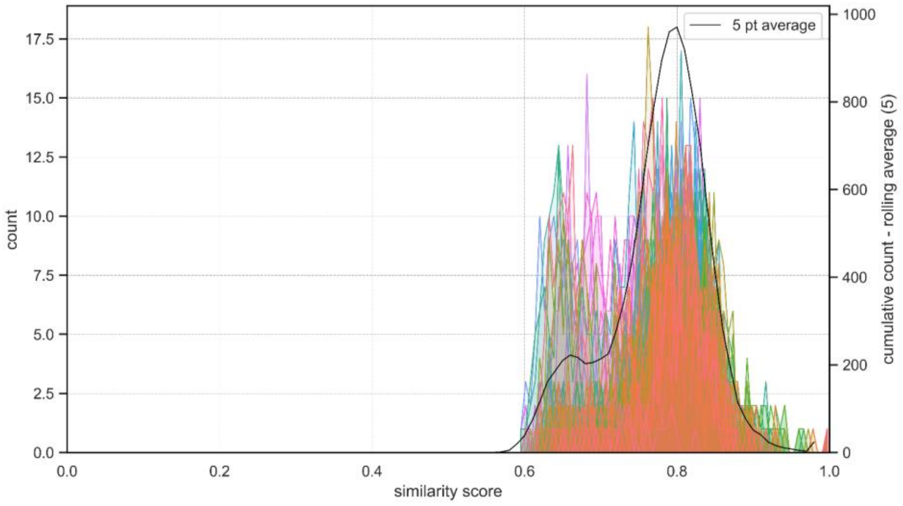


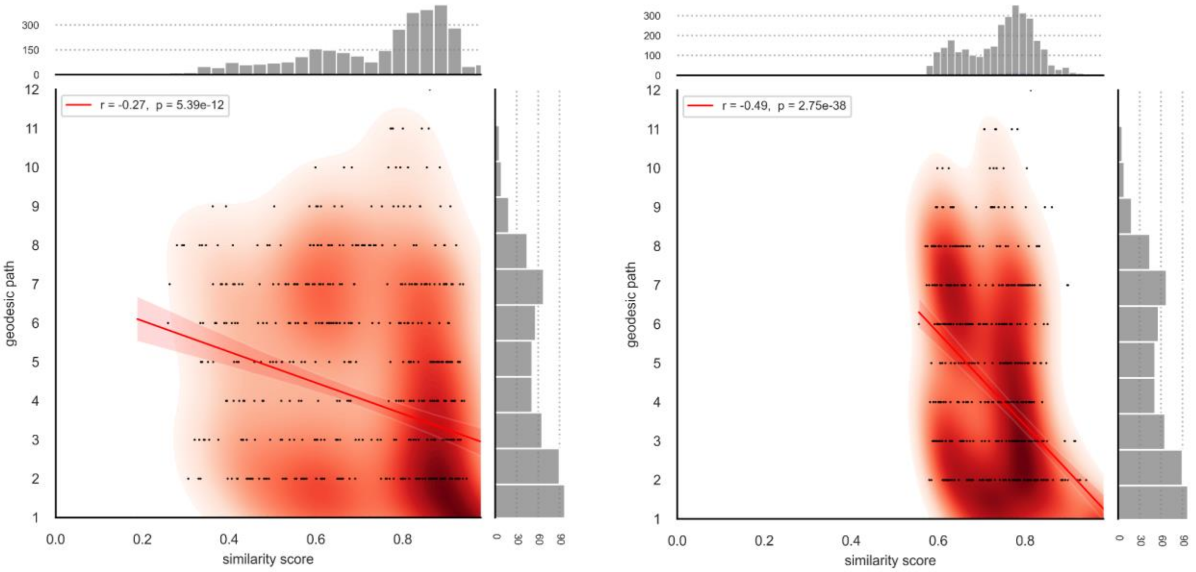
Figure 5.36 ISO 22156 GPT3 similarity score distribution.

5.3.3 Pseudo-Assortativity by Semantic Similarity

Pseudo-assortativity by semantic similarity, as described in Section 4.3.3, was calculated for ISO 22156. Results in Table 5.15 show that for all cases, a negative correlation between geodesic path length and semantic similarity exists which is greater than the expected value based on synthetic networks. Results for ISO22156:2004 (Figure 5.37) show a strong correlation, primarily because of the lack of node pairs connected by paths in the real network (evident in Figure 5.23). Only 620 of possible 3249 directed paths between pairs exist and 57 (9%) of those are guaranteed to have a similarity score and path length both equal to 1. The network structure of ISO 22156:2021 shows a slight negative correlation between geodesic path length and semantically similarity score; greater than expected from random and more strongly correlated than ACI 318 in all cases.

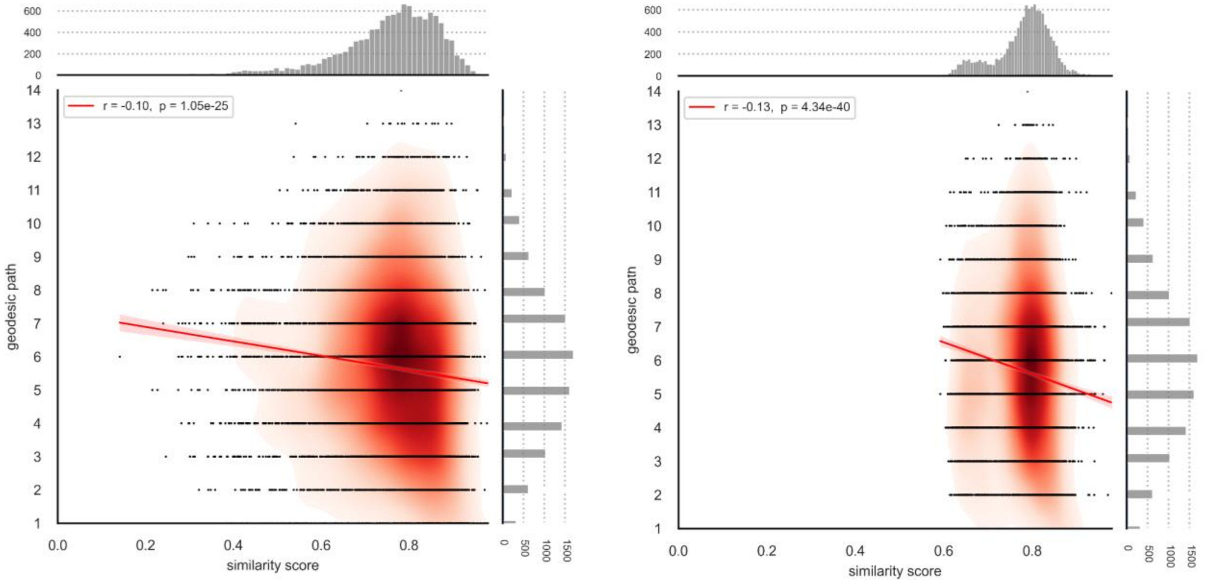
Table 5.15 ISO 22156 pseudo-assortativity by embedding similarity.
(real/random ± standard deviation)

	ISO 22156:2004		**ISO 22156:2021**	
	GPT3	**spaCy**	**GPT3**	**spaCy**
Pearson	-0.487/ -0.134 ± 0.077	-0.272/ -0.033 ± 0.080	-0.124/ -0.047 ± 0.021	-0.101/ -0.057 ± 0.025
Kendall’s Tau	-0.342/ -0.028 ± 0.052	-0.244/ -0.025 ± 0.056	-0.075/ -0.004 ± 0.015	-0.085/ -0.037 ± 0.017
Spearman	-0.462/ -0.044 ± 0.072	-0.339/ -0.039 ± 0.078	-0.105/ -0.007 ± 0.020	-0.121/ -0.051 ± 0.02



(a) spaCy **(b) GPT3**

Figure 5.37 ISO 22156:2004 similarity scores vs geodesic path lengths.



(a) spaCy **(b) GPT3**

Figure 5.38 ISO 22156:2021 similarity scores vs geodesic path lengths.

5.4 Suggestions for Next Revision of ISO 22156

Given the analysis conducted, some suggestions to reduce user-perceived navigational complexity are recommended (in no particular order). All recommendations are made with respect to ISO 22156:2021. Generally, these suggestions assume that forward flow with minimal diversion is desirable by the user.

5.4.1 Reduce Explicit Referencing

The amount of explicit referencing in ISO 22156:2021 appears excessive when compared to other standards analyzed here. Although not directly measured, it is believed that the amount referencing present is not manageable in a workflow. Because of the cognitive limit, end-users can be overloaded by referencing, which can become redundant to the point where it can more easily be ignored. The abundance of references disrupt the natural reading of the standard, as they cannot be interpreted "inline" like plain or natural language. It is also likely that the level of referencing is not sustainable from an authorship perspective, as interdependence between provisions means that one cannot be edited without affecting the others.

For example: Chapters 9, 10, and 12 all exhibit heavy inter-chapter explicit referencing. 12.1- "General [shear panels]" acts as a pointer and explicitly references 12.2.1, 12.2.2, 12.2.3, and 12.3. Clause 12.2 also acts as a pointer and references 12.2.1, 12.2.2, 12.2.3 (the exhaustive list of subclauses in 12.2). At the SWB's discretion, these pointers might be replaced by *"12.2 shall be satisfied."* This is done for the elements of shear panels in the second paragraph of 12.1:*"The bamboo elements of a LCBF shall meet the requirements of this document*".

It is informative here to note that the content of Chapter 12 is slightly tangential to the remaining standard and that Chapter 12 was drafted by a different lead author. The intent in future versions of ISO 22156 is to remove Chapter 12 and develop it into an independent standard. The author of this research was unaware of this while conducting the analyses and it is encouraging that the analyses captured these discontinuities.

5.4.2 Establish a Consistent Implicit Hierarchy

Develop the implicit hierarchy to mimic the mental map of the end-user as closely as possible. This presents both a challenge to the SWB to identify the appropriate end-user to mimic, but also an opportunity to shape the mental map of novice users. Another challenge should be considering the entire design space, to include provisions that are continuing to evolve. The most obvious mental map follows the common design procedures, at which the ISO 22156 standard is largely successful. However, ISO 22156 *"is based on an allowable load-bearing capacity design (ACD)* ***or*** *allowable stress design (ASD) approach...,"* which are presented in parallel; this provides versatility to the document but can be confusing to the user. Parallel sets of explicit references must then link elements of these design strategies together through many chapters.

The first section of most Chapters in ISO 22156:2021 is "General", yet it many cases it functions more as "Miscellaneous"[19]. This is a missed opportunity to guide users along the parallel

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[19] The first section in every chapter being "General" is a requirement of ISO format. Interestingly, the authors of ISO 22156:2021 tried to remove this in many cases; non-subject-matter-expert ISO editors replaced the section in every case.

design 'paths'. For example: Clause 8.1 gives the resistance versus capacity equation (in text format rather than as an [albeit] simple equation; this is another potential issue), stating member capacity is defined by 8.3.1 or 8.3.2. The user's uncertainty about which path to take next could be reduced by including *"for ACD or ASD, respectively."*

The scopes of "General" clauses are also inconsistent; they include pointers, definitions, and/or miscellaneous rules. Again, using Chapter 12 as an example: dimensional requirements are given, although if the requirements were to continue to evolve (as they are sure to), it may be advisable to move such requirements to a subclause – "*geometry*" or similar. Preferably a descriptor would be selected that can also be used for other assembly chapters (trusses, floors, partitions, etc.). In general, it may be detrimental to the growth of the standard to include rules in the general clause, as this does not allow for natural expansion (or requires significant revision of often boilerplate language to accommodate expansion). Explicit references are disproportionately larger from these types of general clauses already; an indicator that the clause should be subdivided where possible. This also allows for other provisions to clearly reference specific portions of these clauses, where needed.

The following structural anomalies in the complete network were observed:

a) Chapter 11, if not dissolved into Chapters 7 and 9, should be re-structured to match other and future component chapters.
b) Chapter 13 may be a subset of Chapter 5; its single inward explicit reference is from 5.7.
c) Chapter 14 may be a subset of 6, as it is referenced heavily (it is the first line in both 6.1 and 6.2) and portions are repeated in 6.1.

Chapters 13 and 14 are both legacy chapters from ISO 22156:2004 and the limitations imposed by ISO necessitated their retention. Once again, it is informative that the analyses conducted in this research identified these discontinuities.

d) As described in Section 5.2.5.2, Section 9.2 appears better suited as a subsection of 9.3, based on explicit referencing.

e) Sections 10.2 and 10.3 may be more appropriate as subsections of 10.4, based on explicit referencing.

f) Section 5.7.2, although related to durability, may be better suited in Chapter 10.9 (which essentially already restates 5.7.2) as identified by Girvan-Newman clustering analysis.

5.4.3 Maintain the Implicit Hierarchy

In order direct forward flow through the standard, backreferencing should be minimized. Many of the back references are to Chapter 6 from Chapters 8 and 9. Provisions in Chapter 6 also show atypical referencing via their high centrality scores. Phrasing typical of 8.3, 8.4, 9.3, and 9.4:

> ***8.3 Flexural member capacity***
>
> *The use of summations of culm capacity or geometric properties in this clause allow for use of multiple culm members.*
>
> ***8.3.1 Flexural capacity determined from component capacity***
>
> *The moment capacity of a member defined from component capacity shall be given by Formula (10):*
>
> $M_r = M$ *(10)*
>
> *Where,*
>
> $M = \Sigma M_i$ *is the sum of the allowable flexural design capacity of the single culms,* M_i*, comprising the member defined in 6.3; or,*
> *M is the allowable flexural design capacity explicitly determined for a multiple culm member defined in 6.3.*

These pointers may be useful but could be eliminated if the equation in Section 6.3 included the summation. There would appear to be no exceptions required to the equation in 6.3 in this case. However, 6.4 ‘Allowable design strength’ would generate an exception for shear, as the summation is not over V_i. Doing the same for 6.5 creates no conflicts. 6.6 creates a single exception (8.4.2).

It is the author’s belief that the standard may benefit from the “‘toolbox’ chapters in the back” format adopted by ACI 318-14, because even though Chapter 6 is *used by* many succeeding Chapters, *it cannot be used before them*. Placing it before the member chapters is similar to defining variables before an equation. That is to say, Chapter 6 is a consolidated subset of ‘tools’ used in the ‘member’ Chapters 8-10 and may be most rationally placed following them, deeper into the implicit hierarchy.

In the sense that modularity can be measured by the explicit reference network, modularity is not maintained in ISO 22156:2021. This is evident by the large proportion of edges (51%) and nodes (82%) in the explicit network, the largest strongly connected component comprising 86% of the network, and the lack of horizontal banding in the complete network heatmap. The implicit network directs flow by logically partitioning the standard into groups of provisions with some semantic similarity or design role and a *progressively narrowing scope*. If explicit references occur from deep within one implicit hierarchy to the top of another, the flow is not well directed, and the scope does not actually narrow. There are likely cycles of requirements in the standard (indicated by the frequency of some 3-node subgraphs), which may or may not be conflicting and may or may not provide a natural end for the user’s task. Ideally the connections between provisions occur in the implicit network, minimizing explicit referencing and maintaining the implicit structure.

An increased proportion of explicit referencing could be attributed to the significant technical expansion of ISO 22156 from 2004 to 2021. The majority of the content in the standard will be used in many design instances. As more niche and detail provisions are included, the SWB should prioritize minimizing referencing out of these provisions.

5.5 Chapter Summary

The International Organization for Standardization (ISO) published the first series of international full-culm bamboo design standards in 2004. These intent-signifying standards were inadequate for holistic design, especially in developing regions. Recently, ISO published revised standards for materials characterization and structural design, ISO 22157:2019 and ISO 22156:2021, respectively. The new standards permit allowable capacity design and allowable stress design while preserving the ability to design structures based on local generational experience. The authors of the new ISO standards aimed to minimize complexity to make the documents more accessible and increase the adoption of the standards worldwide. This chapter reports an analysis of ISO 22156, providing guidance and a benchmark for future versions of the standard. The methods used for the analysis are the same as those presented in Chapter 4.

Network analysis techniques were used to study the connectivity of ISO 22156:2004 and ISO 22156:2021. First, an overview of the basic features of the reference networks extracted from these two standards was presented. Next, node centrality, a measure of its importance to the network, was explored using various centrality metrics including degree distribution, PageRank centrality, HITS centrality, betweenness centrality, and closeness centrality.

ISO 22156:2021 has a greater proportion of explicit nodes and edges compared to ISO22156:2004 and both versions of ACI 318 studied in Chapter 4. Excessive referencing is believed to be detrimental to user experience. Excessive explicit referencing may be a symptom of a poor implicit structure, which could be exacerbated by the rapid technical evolution of the standard. The standard has all of the fundamental pieces necessary for design, but lacks detailing provisions that may reduce the proportion of explicit references in the future. Additionally, the single largest strongly connected component present in ISO 22156:2021, containing 86% of nodes, suggests that the implicit hierarchy is not well maintained and 'flow' in the network is not well directed.

Centrality analysis may be more useful in identifying problem areas within the standard than identifying ‘important’ provisions. The results of the centrality analysis indicate that nodes with high betweenness scores represent provisions common to many design instances in ISO 22156:2021, which is consistent with betweenness results for ACI 318. The degree distribution for ISO 22156:2021 displays a heavy tail with positive skew, which may indicate decreased modularity and an abundance of provisions serving navigational functions (the latter is illustrated by various examples in this chapter). Unlike the PageRank results for ACI 318, provisions with high PageRank centrality in ISO 22156:2021 are essential to design and would nearly all be used in most design instances. Similarly, closeness centrality scores for the ISO 22156:2021 complete network are representative of provisions users might find important for design. Closeness centrality distributions for ISO 22156:2021 indicate that the explicit network plays a significant role in the structure of the complete network.

The clustering coefficients in the complete reference network of ISO 22156:2021 indicate disruption to the implicit hierarchy, as provisions with low clustering scores in the implicit network of ISO 22156:2021 are not preserved in the complete network. Motif detection of subgraphs with 3, 4, and 5 nodes was performed for ISO 22156:2004 and ISO 22156:2021 implicit and complete networks. The results indicate that ID 38, the 'feed-forward loop', is fundamental to the networks based on the implicit network definition adopted in the study. Motif ID 108, the only additional 3-node motif found in the ISO 22156:2021 complete network indicates explicit references generate backreferences. An in-depth study of motifs and their functions in standards may be warranted.

Structural clustering of provisions was investigated using the Girvan-Newman algorithm with edge betweenness as the decision property. Results show high association with provisions' parent chapters. In ISO 22156:2021, Clause 5.7.2, the single provision not clustered with its parent chapter, is suspected of being misplaced. k-means clustering by provision embedding was also pursued for ISO 22156:2004 and ISO 22156:2021 using spaCy and GPT3 embeddings. GPT3 embeddings tend to cluster chapter titles together (regardless of meaning), possibly due to the provision length or syntactic qualities. Still, GPT3 clusters had the highest average association with other clustering methods (including the provision parent chapters), while spaCy clusters have poor to moderate associations in all cases. Approximate meanings of the clusters were investigated by examining the terms closest to the centroids of each cluster in the spaCy embedding space. Many of the term clusters are representative of chapters or sections in ISO 22156:2004, but less so for ISO 22156:2021, possibly due to larger provisions and larger clusters.

Similarity analysis was conducted between all pairs of provisions in ISO 22156:2004 and ISO 22156:2021 using both spaCy and GPT3 embeddings. Results for ISO 22156:2021 follow similar trends as those found in ISO 22156:2004 and ACI 318, with spaCy embeddings usually differentiating between titles and typical provisions with more text, and GPT3 embeddings showing clear differentiation between titles and typical provisions while reporting high inter-chapter similarity scores. Overall, the findings suggest that more refined natural language models are needed to classify the provisions of engineering standards, parse relationships between them, or suggest a comprehensive workflow to an end-user on demand.

Finally, based on the results of the network analysis, guidance and specific suggestions for revising ISO 22156:2021 to reduce user perceived navigational complexity were presented. The suggestions center around reducing uncertainty by developing a forward flow through the standard that mimics the mental map of the design space held by a representative end-user. The actionable guidance focuses on establishing a consistent implicit hierarchy that is natural to the end-user and maintaining that hierarchy by minimizing explicit referencing.

6.0 Discussion, Conclusions, and Recommendations for Future Investigations

The primary objective of this dissertation was to develop an understanding of user-perceived complexity in building design standards, and to identify tools and strategies to measure and manage this. The concept of complexity was explored, and an operational definition was identified that is dependent on the ability of the standard to perform as the user requires it to. Complexity stemming from navigation in construction standards appeared ripe for study due to advancements in NLP and network analysis. The 2014 reorganization of ACI 318 provided a unique opportunity to draw comparisons between standards that are nearly identical, from a technical standpoint, but are organized quite different.

The study first surveyed user perceptions of the structural revision of ACI 318-11 to ACI 318-14, and then characterized the reference networks of those standards to identify features associated with positive and negative user experiences. Based on that analysis, a case study was conducted with a developing design standard, ISO 22156:2021, to establish a baseline and provide suggestions to mitigate user-perceived navigation-related complexity. The following sections provide discussion and conclusions of this research as well as recommendations for future investigations.

Although this work is limited to building design standards, an opportunity exists to leverage network analysis to mitigate navigational complexity in other types of standards as well. The most essential task is to first understand the needs and expectations of end-users of the standard. In particular, the SWB must understand how users perceive the design space (or conformance space) such that the standard can be organized in a logical way. The SWB can carefully conduct surveys and interviews of end-users, like those presented here. More effective means of stakeholder engagement (and expectations) must be investigated for use with NOCMAT standards. Once the design space is mapped, the SWB should closely align the implicit network to this mapping and establish a forward flow for most design instances. Explicit references should be minimized by effectively using the implicit network. Toolbox chapters are useful for reducing repetition and can provide natural stopping places for design instances. Deep hierarchies should be preserved in the complete network to again provide natural stopping places. Network analysis techniques described in this dissertation can then be applied to existing and proposed structures to measure the topological features. Early in the standard-writing process, centrality and geodesic paths can provide insight into atypical reference structures and concentrations within the proposed structures. Alternatives that maximize features 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, are likely to enhance ease-of-use and reduce complexity. 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.

6.1 Complexity

Axiomatic design, described in Chapter 2, was used in this dissertation as a framework to understand complexity, but was not applied rigorously to the design of design standards due to resource constraints. However, its success in applications across other fields indicates that it may be a promising tool for managing complexity in standards. The view that the complexity (and performance) of a design standard must be defined in the functional domain, not the physical domain, makes the user experience central to improving the standard. Navigational complexity was selected, in-part, because uncertainty is readily apparent in a navigational context. For complexities tied to other qualities of the standard, this relationship is not as clear and each may warrant their own investigation. Table 2.1 identifies other essential quality dimensions identified by Angelino et al. (2014), a useful starting point for further investigations. In all cases, more data from users would be helpful in determining how features (e.g., commentary and commentary location, plain language, external references, repetition, equations vs text vs diagrams, etc.) of a standard and other SWB decisions affect performance. This process is likely to identify measurable indicators of performance which can be used to improve user experience.

Additionally, the four design domains described in axiomatic design align well with regulatory domains (Figure 2.3) identified by Coglianese (2016). The zigzagging decomposition process, described in Suh (2001), may be well-suited to understanding gaps between regulations and the design space. It is apparent from cursory observations that design standards are a mix of three types of rules: performance (functional domain), prescription (physical domain), and management (process domain). The last of which is often conflated with prescriptive rules or considered with prescription as “means-based” rules. Management rules are rarely directly considered but determine what design methodologies are allowable, for example. The recognition of these rule types as being hierarchically integrable, rather than mutually exclusive, may provide SWBs with prospective to standardize challenging tasks, entities, and processes. That is, when a performance requirement cannot be decided upon for a particular detail, often a prescriptive requirement based on past experiences is implemented. When a prescriptive requirement cannot be easily implemented, the design process can be broadened (i.e., ‘design by testing’). Moreover, at any stage the SWB can move up to a super-(function/component/process) or down to a sub-(function/component/process) that is regulatable, provided they are sure to not overlap or leave gaps in the hierarchy. A gap in performance may occur if the ‘design-by-testing’ methodology is not representative of in-service conditions, for instance.

6.1.1 User Perception Survey

The importance of understanding the intended user of a standard cannot be understated. Design standards exist to serve many objectives, but none of them are achievable if the standard cannot be properly decoded by the user. The ‘public’ comment phase that is built into many standards’ revision cycles provides feedback of only limited scope and quality in this regard. Angelino (2019) developed guidance for Highways England and Eurocode standards after identifying a set of quality dimensions based on stakeholder surveys and interviews. The survey of ACI 318 users reported in Chapter 3 shows that respondents can discern whether these qualities have been affected by a revision in the standard and if those qualities were favorable to the standard. The seemingly incongruent results of the two portions of this survey also highlights the need to mitigate the effects of user bias and subjective experiences when surveying users. The survey was limited by the small sample size and unrepresentative demographics, which does not allow for statistically significant conclusions about the population of users to be drawn. Nonetheless, the results indicated that the 2014 revision of ACI 318 resulted in perceived improvements to particular traits of the standard that respondents found important.

The level of survey participation highlights that gaining useful feedback from users can be challenging, as mentioned by others (Nethercot 2012). Ad-hoc committees' actions such as those enacted by ACI 318 to study its 2014 revision require generous institutional momentum. The only standing effort to understand how users interact with the code identified in the North American literature is a recurring trial design problem hosted by the Structural Engineering Institute (SEI) Design Practices Committee (E. Nagy, personal communication March 3, 2021). Using the trial problems, the committee has developed a better understanding of how end-users use ASCE 7 and has revealed errors in ASCE 7-95, -05, and -10. Among the more interesting findings are that design assumptions are most strongly associated by office (not by region), that common sources of errors for users are misreading tables, maps, figures (such as the very complex figures associated with ASCE 7 wind loading provisions) and missed footnotes. Given these findings and that code complexity is seen as a problem to many people in the AEC industry, it is perhaps surprising that there is not a concerted effort to measure and improve user experiences with common design standards. Sustained future research efforts utilizing trial design problems are expected to be fruitful.

Although paper and paper-facsimile (PDF) based standards dominate the industry today, we are likely to see greater transition towards digital web-based media. The issue of structure, however, will not be alleviated by this transition. The structure of a standard is a reflection of the relationships between the requirements of the standard. In fact, understanding these relationships (i.e., the structure of the standard) may become more important in providing a smooth transition to digital since users will ***expect*** easier navigation with the digital format. Suggesting likely paths through the standard via related topics and provisions could greatly aid end-users, or hopelessly bog them down.

6.1.2 Future Investigations

- A survey of applications of axiomatic design or other quality management schemes to codified documents. How are various requirements measured and related?
- A full axiomatic design decomposition of a standard and its design space.
- Ways to measure value of reducing complexity for users, preferably in units of cost.
  - How much additional would users pay for a standard that was ‘easy-to-use’?
- Understanding user experience with common features of standards.
  - Which features are SWB specific and why?
  - How might we facilitate the transition to application-based standards.
- User-oriented standards: barriers and opportunities in presenting unique versions of a standard to a particular user.
  - SWB vs internal office vs third party applications.
- Understanding user navigation by tracking them while applying various standards.
  - Potentially during standardized testing in US practice.
  - Trial problem format.
- Implementing trial design problems during comment phase.
- Criteria for refining an equation or process.
  - Precision vs simplicity and the opportunity for error due to increased information content.
- A human-centered design approach to standards.
  - Non-conventional stakeholder engagement: ways to better understand and deliver to stakeholders needs.
  - How does the standard influence the design workflow? How might we minimize the impact of the standard without reducing technical content/requirements?
- Criteria to delete a requirement. What are *minimum* requirements?

6.2 Network Analysis

Networks are a versatile abstraction for many systems and have therefore been studied under many contexts. The research presented in this study shows that network analysis can provide useful information about the structure of a standard to the SWB. The author believes that there are many uninvestigated applications for network analysis in the context of codified documents.

Ensuring the representativeness of large networks can be challenging, but in most cases isolated errors are thought to have little effect on network features. Type I and II errors can occur in the reference extraction process; these can be onerous to identify and correct. For example, a known Type II error occurs with a phrase such as "*Chapters 4-8*" is encountered, because the pattern matching only identifies a reference to Chapter 4. In this study "boilerplate" chapters in standards were excluded from analysis partially because of their tendency to generate Type I errors when included. Tables and figures, which typically do not include references, were excluded during extraction because they often span the entire page width in ACI 318 and generate Type I errors due to the side-by-side commentary format. Generally, the extraction process adopted here performs well with limited human correction required. It is also simple to develop the network edge list manually if a SWB wished to do so (for instance), although this would be time-consuming.

Simple network features such as the proportion of forward to backward explicit edges are better indicators of navigational complexity than the number of pages or provisions. Specifically, when backreferencing is more common than forward referencing, the implicit network is unlikely to mimic users' mental maps, which is suspected to hinder navigation. In axiomatic design terms, the information content is higher in a standard where the implicit layout does not follow users' mental map because the users need additional information (i.e., explicit references) from the standard to navigate it. Complexity is inherently greater in such a standard. It is worth emphasizing that the map of the design space does not necessarily equate to the typically understood engineering design workflow.

The network definition adopted here does not capture ‘silent references’ between provisions that merely mention shared datum such as variables, noun phrases, or general topics. Each network could be refined to include the individual datum within each node, although it would require a more advanced extraction process, a more robust network definition and thoughtful data management since the relation-actions between datum vary widely. Some schemes discussed in Section 2.4.1 may be able to represent the standard at this granularity.

Centrality scores can identify nodes and clusters of nodes in a standard with atypical connectivity. These nodes typically serve functions that others do not and may be ‘important’ to a standard or indicate areas in need of attention [improvement] by the SWB. Some centrality scores presented here show little worth due to inconsistent results or results that are not naturally interpretable in the context of standards. Centrality distributions can be interpreted to gain insight into the structure of standards; however, most scores are sensitive to the size of the network and comparisons between networks of different sizes carry little meaning.

Motifs in standard networks may be a promising area for study, as they appear to carry functional roles in the standard, robust methods exist to identify and measure them, and almost no literature has been identified investigating motifs in the context of codified documents (an abundance of literature exists in the field of microbiology, for instance). Moreover, understanding the suppression or under-expression of subgraphs in the standards studied here may be useful in understanding the success of some standards. It is believed that identifying and reducing subgraphs with cyclic referencing structures could improve user-navigation and possibly decouple provisions in the standard.

User navigation was simply modeled with geodesic paths, although actual user navigation was not studied here. It would be useful to actively track users while they solve trial design problems to identify desire lines through the standard. Such data may become easier to obtain with app-based standards such as ACI 318 Plus although benchmarking will also be required. The plots of geodesic paths presented in Sections 4.2.5 and 5.2.5 are admittedly challenging to interpret at first glance but provide tremendous insight into the connectivity of the reference networks studied here. Backreferencing, hotspots, modular sections, and other indicators of navigational complexity can all be observed on these plots.

Clustering provisions based on edge-betweenness using the Girvan-Newman algorithm showed promising results for the smaller ISO standards but were more challenging to interpret for the larger ACI standards. Many chapters from each network tended to cluster together, some more strongly than others. 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 identified by the algorithm. In these cases, the SWB might consider relocating these provisions.

6.2.1 Future Investigations

- Means to establish, manage, and investigate an information network representation of a standard with a greater level of granularity.

- A broad study of reference networks to understand feature trends relating to maturity, size, SWB, etc.
- Methods to more accurately model users of a standard in a reference network.
- Understanding motif expression, suppression, and functions.
- Suggesting provisions related to a design instances using network properties.
- Expanding the network and similar analysis to multiple standards.

6.3 Natural Language Processing

NLP was used here to lessen the human resource burden of constructing the reference network and to explore semantic relations between provisions. As described previously, some issues of text extraction were challenging and potentially anomalous. Neither model used is this study (spaCy or GPT3) was tuned to the civil engineering knowledge domain due to the lack of available corpora; in theory, both models will provide more accurate results if so tuned. A civil engineering corpus could be used to fine-tune a natural language model to domain specific terms and would be immensely useful in downstream tasks such as categorizing, suggesting, and name entity labelling. Labels could be used to tag granular datum. Such datum could be mapped across the standard and/or through external references to identify interactions at a refined level of detail. A notable challenge with this strategy from a network perspective is that the nodes become containers for the entire text of the provision and edges are property rich but potentially ambiguous in direction. A robust multi-digraph network definition would be required to manage these relations.

In the future, fine-tuning a language model on a corpus will likely be unnecessary for extraction, as context models are becoming large enough to capture niche semantic relations. These models will almost certainly be used in standard writing in the form of grammar and spell checkers, however they could be also used for translation, summarization, checking logical consistency, ordering, or any number of useful tasks.

Limitations of embedding averaging was discussed in Section 2.6.2. The embedding of the provision is affected by the length of the provision, an obvious drawback. Because of this and potentially other syntactic features, the embeddings are biased by the structure of the provision (e.g., whether it be a title or paragraph form) and separating these is likely to improve results of the analysis presented here. The similarity score distributions appear to be mixtures (potentially Gaussian), which could be parsed into separate distributions to facilitate more representative results. Overall, this portion of the analysis was not particularly fruitful, but does demonstrate that off-the-shelf natural language models are improving rapidly and even those used here could potentially be used to categorize provisions by chapter with reasonable accuracy.

6.3.1 Future Investigations

- Investigate means to increase granularity of network representations, while minimizing human resources.

6.4 Standard Development

While the author strived to set boundaries on the analyses conducted here such that assumptions and conclusions were valid when considering both ACI 318 and ISO 22156 standards, the standards admittedly share little in common. Each of the standards represents a unique level of maturity defined by the quantity, detail, and organization of technical content which cannot be separated from the magnitudes and histories of their respective industries. The intent for each revision was different; ACI 318-14 focused on organization of a standard that many felt had become cumbersome. On the other hand, ISO 22156:2021 focused on increasing technical content to enable an entire design workflow for a relatively limited design space: primarily 1 and 2 story residential construction. The standards were developed under different governing bodies who set their own priorities and rules for the standardization process to include styling, voting, public comment, etc. ISO standards are developed for and by international stakeholders and the standard writing process covers all manner of industries, while ACI standards are developed largely for North American concrete practice.

A major difference in the text of the standards stems from ISO not allowing accompanying [non-mandatory] commentary[20], when ACI allows side-by-side commentary. 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.

The differences listed here are substantial and, accordingly, not all comparisons between the standards studied are valid. However, the structures of the standards can be represented as networks and serve similar functions. The structure allows the user to find the provisions needed to satisfy a design instance by connecting provisions with related concepts. Because the structures serve similar purposes and representations, comparisons and claims respecting network science

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[20] The authors of ISO 22156 attempted to overcome this limitation to some extent by including five nonmandatory “informative” annexes.

appear to be valid. This study suggests that network analysis is a useful and accessible tool for SWB to manage navigational complexity, particularly if paired with a mechanism to gain user feedback.

Appendix A Perception Survey

This Appendix reports the entire online perception survey. Raw results are archived and available for inspection in the supporting documentation.

Survey:

Q1.1 The purpose of this research study is to develop an understanding of the complexity in building codes and standards. The reorganization of ACI 318 *Building Code Requirements for Structural Concrete* in 2014 presents a unique opportunity to assess and learn from professionals' experience using and transitioning between two distinct formats of a single code document. Therefore, the purpose of this questionnaire is to better understand your experience using **ACI 318**. If you are willing to participate in our (approximately 10-12 minute) questionnaire, you will be asked about your education background, general questions about your professional position as it relates to the use of **ACI 318** and your perceptions of the utility of either or both of **ACI 318-11** and **ACI 318-14**. You will be also asked your opinion of the transition between the **2011** and **2014** versions of **ACI 318**.

There are no foreseeable risks associated with this project, nor are there any direct benefits to you. This is an entirely anonymous questionnaire; your responses will not be identifiable in any way. All responses are confidential, and the results will be securely maintained in password encrypted files. Your participation is voluntary, and you may withdraw at any time. This study is being conducted by Professor Kent A. Harries, who can be reached at kharries@pitt.edu, if you have any questions.

This questionnaire focuses on your ability to successfully utilize **ACI 318** before and after the reorganization between the **2011** and **2014** editions. We appreciate your candid responses, which will support our research into professional perceptions of Codes and Standards.

In this survey, we refer to ACI 318 *Building Code Requirements for Structural Concrete* in general (without specifying a year) as **ACI 318**. Specific editions of **ACI 318** will be referred to as follows: **ACI 318-11** and **ACI 318-14**.

The authors of the survey recognize that users will utilize **ACI 318** in different ways. When completing this survey, we ask that you keep in mind **your typical** use of the document.

Please indicate which edition you have experience using and are willing to provide feedback about:

ACI 318-11 *Building Code Requirements for Structural Concrete* (1)
ACI 318-14 *Building Code Requirements for Structural Concrete* (2)
Both (3)
Neither (4)

Q2.1 Please indicate your highest education attainment:

High School (1) ,Associate's Degree (2), Bachelor's Degree (3), Master's Degree (4) , PhD (5)

Q2.2 Please indicate your professional licensure (if any):
Professional Engineer (PE, PEng, CEng, or similar) (1) , Structural Engineer (SE) (2) , Engineer in Training (EIT) (3) , Other (4), None (5)

Q2.3 In which country do you mostly practice?
▼ Afghanistan (1) ... Zimbabwe (195) [typical notation for pull-down menu]

Q2.4 In which state do you mostly practice?
▼ Alabama (1) ... Wyoming (52)

Q2.5 In which province do you mostly practice?
▼ Alberta (1) ... Yukon (13)

Q2.6 Please indicate your primary areas of concrete-related practice: (Select all that apply)
Design (1) , Construction (2) , Material Production (3) , Research (Academic or Industry) (4), Education (5) , Code Enforcement (6) , Facility Management (7) , Other: (8)

Q2.7 Have you served on ACI Committee 318 at any time?
Yes (1) , No (2)

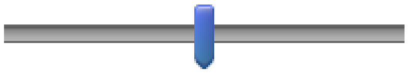
Q2.8 Please indicate your concrete industry experience: (Years)
0 - 5 (1) , 6 - 10 (2) , 11 - 15 (3) , 16 - 20 (4) , 20 + (5)

Q2.9 Please indicate your experience using **ACI 318**: (Years)
0 - 5 (1) , 6 - 10 (2) , 11 - 14 (3) , 15 - 20 (4) , 20 + (5)

Q2.10 Over the course of a typical project that requires **ACI 318**, approximately how often do you consult **ACI 318**?
Multiple times a day (1), Daily (2) , A few times a week (3) , A few times a month (4), Rarely (5)

Q2.11 Identify any supplemental material regularly used to support your use of **ACI 318** : (Select all that apply)
The Commentary to **ACI 318** (1) , Design Guides (2) , Textbooks or course notes (3) , Personal notes (4) , Custom spreadsheets or similar (e.g. Excel or Mathcad) (5) , Commercially-available computer programs (6), Other: (7)

Q2.12 For a typical design, estimate your reliance on **ACI 318** versus other design tools to ensure all required provisions are satisfied for a job: (%)
0% - Always use other design tools, 100% - Always use **ACI 318**

	0 20 40 60 80 100%
0 to 100% ()	

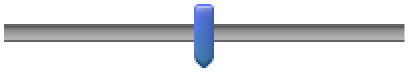
Q2.13 Does your practice **regularly** include seismic design? (**ACI 318-11 Chap. 21** or **ACI 318-14 Chap. 18**)
Yes (1) , No (2)

Q2.14 Do you consider yourself fluent in English?
Yes (1) , No (2)

Q3.1 Please indicate your experience using **ACI 318-14**: (Years)
0 - 2 (1), 2 - 4 (2), 4+ (3)

Q3.2 On which media do you typically use ACI 318-14?
Digital - Personal Copy (e.g. PDF) (1), Digital - Shared Copy (multi-user/multi-site) (2) , Paper - Personal Copy (3) , Paper - Shared Copy (4)

Q4.1 Considering <u>**only**</u> ACI 318-14, how confident are you in your interpretation of requirements? (%) ,
0% = Not Confident , 100% = Extremely Confident

	0 20 40 60 80 100%
0 to 100% ()	

Q4.2 Considering <u>**only**</u> ACI 318-14, rate the following tasks:

	Difficult (1)	Slightly Difficult (2)	Neutral (3)	Slightly Easy (4)	Easy (5)
Identify which provisions are required (1)					
Locate a required provision (2)					
Locate all required provisions (3)					
Confidently satisfy a required provision (4)					
Confidently satisfy all required provisions (5)					

Q4.3 Considering <u>**only**</u> ACI 318-14, how quick or slow is it to **identify which provisions are required** for a job?
Slow (1) , Slightly slow (2) , Neither quick nor slow (3), Slightly quick (4) , Quick (5)

Q4.4 Considering <u>**only**</u> ACI 318-14, how quick or slow is it to **locate the required provisions** for a job?
Slow (1) , Slightly slow (2) , Neither quick nor slow (3), Slightly quick (4) , Quick (5)

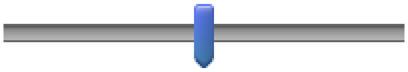
Q4.5 Considering <u>**only**</u> ACI 318-14, rate the following tasks:

	Difficult (1)	Slightly Difficult (2)	Neutral (3)	Slightly Easy (4)	Easy (5)
Understand the scope of a provision (1)					
Understand the language in a provision (2)					

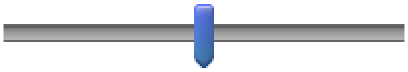
Navigate from one provision to another it references (3)	
Navigate back from a referenced provision to the originating provision (4)	
Design (or analysis) from beginning to end (5)	

Q4.6 Considering **only** ACI 318-14, how quick or slow is it to **navigate between** referenced provisions?
Slow (1) , Slightly slow (2) , Neither quick nor slow (3), Slightly quick (4) , Quick (5)

Q4.7 Considering **only** ACI 318-14, estimate the likelihood of **you** correctly interpreting a provision: (%)
0% = Always incorrect , 100% = Always correct

	0 20 40 60 80 100%
0 to 100% ()	

Q4.8 Considering **only** ACI 318-14, estimate the likelihood of **the average user** correctly interpreting a provision: (%) 0% = Always incorrect , 100% = Always correct

	0 20 40 60 80 100%
0 to 100% ()	

Q5.1 Please comment on your experience (challenges, benefits, etc.) transitioning from **ACI 318-11** to **ACI 318-14**:

Q5.2 How, if ever, has **ACI 318** failed to meet your expectations?

Q5.3 Any additional comments: (What have we missed?)

Q5.4 Advancing will end this survey, please finalize all answers before continuing.

Q6.1 Please indicate your experience using **ACI 318-11**: (Years)
0 - 4 (1) , 5 - 8 (2) , 8+ (3)

Q6.2 On which media do you typically use ACI 318-11?
Digital - Personal Copy (e.g. PDF) (1) , Digital - Shared Copy (multi-user/multi-site) (2) , Paper - Personal Copy (3) , Paper - Shared Copy (4)

Q7.1 Considering **only** ACI 318-11, how confident are you in your interpretation of requirements? (%)
0% = Not Confident , 100% = Extremely Confident

	0 20 40 60 80 100%

0 to 100% ()	

Q7.2 Considering **<u>only</u>** ACI 318-11, rate the following tasks:

	Difficult (1)	Slightly Difficult (2)	Neutral (3)	Slightly Easy (4)	Easy (5)
Identify which provisions are required (1)					
Locate a required provision (2)					
Locate all required provisions (3)					
Confidently satisfy a required provision (4)					
Confidently satisfy all required provisions (5)					

Q7.3 Considering **<u>only</u>** ACI 318-11, how quick or slow is it to **identify which provisions are required** for a job?
Slow (1) , Slightly slow (2) , Neither quick nor slow (3), Slightly quick (4) , Quick (5)

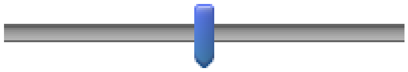
Q7.4 Considering **<u>only</u>** ACI 318-11, how quick or slow is it to **locate the required provisions** for a job?
Slow (1) , Slightly slow (2) , Neither quick nor slow (3), Slightly quick (4) , Quick (5)

Q7.5 Considering **<u>only</u>** ACI 318-11, rate the following tasks:

	Difficult (1)	Slightly Difficult (2)	Neutral (3)	Slightly Easy (4)	Easy (5)
Understand the scope of a provision (1)					
Understand the language in a provision (2)					
Navigate from one provision to another it references (3)					
Navigate back from a referenced provision to the originating provision (4)					
Design (or analysis) from beginning to end (5)					

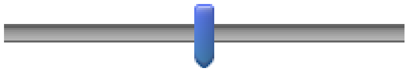
Q7.6 Considering **<u>only</u>** ACI 318-11, how quick or slow is it to **navigate between** referenced provisions?
Slow (1) , Slightly slow (2) , Neither quick nor slow (3), Slightly quick (4) , Quick (5)

Q7.7 Considering <u>only</u> ACI 318-11, estimate the likelihood of you correctly interpreting a requirement:
(%) 0% = Always incorrect , 100% = Always correct

	0 20 40 60 80 100%
0 to 100% ()	

Q7.8 Considering **only** ACI 318-11, estimate the likelihood of **the average user** correctly interpreting a requirement: (%)

0% = Always incorrect , 100% = Always correct

	0 20 40 60 80 100%
0 to 100% ()	

Q8.1 Please indicate which edition of **ACI 318** better meets the following requirements:

	ACI 318-11 (1)	Usually ACI 318-11 (2)	Neutral (3)	Usually ACI 318-14 (4)	ACI 318-14 (5)
Required provisions can be easily identified (1)					
Required provisions can be quickly identified (2)					
Scope of provisions is clear (3)					
Language in provisions is clear (4)					
Provisions are succinctly written (5)					

Q8.2 Please indicate which edition of ACI 318 better meets the following requirements:

	ACI 318-11 (1)	Usually ACI 318-11 (2)	Neutral (3)	Usually ACI 318-14 (4)	ACI 318-14 (5)
Provisions are presented logically (1)					
Provisions are not missing (2)					
Scope of Code enables most designs (3)					
Provisions are logically-connected (4)					
Requires greater knowledge of first principles (5)					
Minimal risk of misinterpretation (6)					

Q8.3 The next 3 questions are general in nature and do not directly relate to **ACI 318**.

Considering Building Codes/Standards generally and what makes them successful, please rank the following traits in order of their importance:

(Drag and drop to rearrange)
______ Provisions are reliably correct (1)
______ Minimal risk of misinterpretation (2)
______ Code can be applied in numerous applications by users of different skill levels (3)
______ Users understand how to satisfy provisions (4)
______ Users understand why provisions are required (5)
______ Provisions enable economic design/construction (6)
______ Provisions can be quickly applied (7)

Q8.4 Considering Building Codes/Standards generally and what makes them successful, please rank the following traits in order of their importance:

(Drag and drop to rearrange)
______ Required provisions are quickly and easily identified (1)
______ Code is presented logically (2)
______ Provisions are sufficient for design at hand (3)
______ Users understand which provisions are required (4)
______ Provisions enable economic design/construction (5)
______ Provisions can be quickly applied (6)
______ Provisions are logically-connected and easy to follow (7)

Q8.5 Considering Building Codes/Standards generally and what makes them successful, please rank the following traits in order of their importance:

(Drag and drop to rearrange)
______ No need to reference other documents (1)
______ Provisions provide for sufficiently safe designs (2)
______ Provisions clearly identify responsible stakeholders (3)
______ A change in one provision does not affect others (4)
______ Provisions are not outdated by technology or practice (5)
______ Provisions enable economic design/construction (6)
______ Provisions can be quickly applied (7)

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