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Unpacking ambiguity in building requirements to support automated compliance checking

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Abstract:	In the architectural, engineering and construction (AEC) industry, manual compliance checking is labour-intensive, time-consuming, expensive and error-prone. Automated compliance checking (ACC) has been extensively studied in the past 50 years to improve the productivity and accuracy of the compliance checking process. While numerous ACC systems have been proposed, these systems can only deal with requirements that include quantitative metrics or specified properties. This leaves the remaining 53% of the building requirements to be checked manually, mainly due to the ambiguity embedded in them. In the literature, little is known about the ambiguity of building requirements, which impedes the accurate interpretation and automated checking of these requirements. This research thus aims to address this issue and establish a taxonomy of ambiguity. Building requirements in Health Building Notes (HBN) are analysed using an inductive approach. The results show that some ambiguous clauses in building requirements reflect regulators' intention, while others are unintentional, resulting from the use of language, tacit knowledge and ACC-specific reasons. This research is valuable for compliance-checking researchers and practitioners by unpacking ambiguity in building requirements, which lays a solid foundation to address ambiguity appropriately.
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The journal requires that all submissions fall within its aims and scope, explained here. Please explain how your submission fits the journal's aims and scope.	Journal of Management in Engineering accepts papers discussing information and communication issues in civil engineering. This paper discusses a particular characteristic of design regulations that hamper communications in design compliance checking. It outlines the obstacles to computer-aided automated compliance checking. The research uses grounded theory methodology to explore a phenomenon in design regulations. This approach has been adopted in a paper published in this journal. Zhou, Z., Irizarry, J., Li, Q., and Wu, W. (2015). "Using grounded theory methodology to explore the information of precursors based on subway construction incidents." Journal of Management in Engineering, 31(2), 04014030.
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Unpacking ambiguity in building requirements to support automated compliance checking

Zijing Zhang[1]; Ling Ma, Ph.D.[2]; and Nicholas Nisbet[3]

Abstract

In the architectural, engineering and construction (AEC) industry, manual compliance checking is labour-intensive, time-consuming, expensive and error-prone. Automated compliance checking (ACC) has been extensively studied in the past 50 years to improve the productivity and accuracy of the compliance checking process. While numerous ACC systems have been proposed, these systems can only deal with requirements that include quantitative metrics or specified properties. This leaves the remaining 53% of the building requirements to be checked manually, mainly due to the ambiguity embedded in them. In the literature, little is known about the ambiguity of building requirements, which impedes the accurate interpretation and automated checking of these requirements. This research thus aims to address this issue and establish a taxonomy of ambiguity. Building requirements in Health Building Notes (HBN) are analysed using an inductive approach. The results show that some ambiguous clauses in building requirements reflect regulators' intention, while others are unintentional, resulting from the use of language, tacit knowledge and ACC-specific reasons. This research is valuable for compliance-checking researchers and practitioners by unpacking ambiguity in building requirements, which lays a solid foundation to address ambiguity appropriately.

Keywords: Ambiguity, Automated Compliance Checking, Building Requirements

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Introduction

In the construction industry, before the commencement of the construction stage, the building design must meet the requirements in regulatory documents to get approval (Zhang et al. 2022). Compliance checking is an important step where the building design is checked against standards, requirements, and codes in regulatory documents (Eastman et al. 2009; Soliman-Junior et al. 2021; Zhang et al. 2023). It is a complex process that involves various actors, such as designers, domain experts and regulators. Traditionally, the compliance checking process is conducted manually, which is expensive, time-consuming, and prone to errors (Han et al. 1998; Macit İlal and Günaydın 2017). As a result, project delays or poor building performance are prevalent (Eastman et al. 2009; Macit İlal and Günaydın 2017; Preidel and Borrmann 2016).

To address these issues, numerous automated code compliance checking systems have been developed by researchers and practitioners, mainly including hard-coded systems (Jiang and Leicht 2015; Solibri 2022; Solihin et al. 2004), language-driven methods (Kim et al. 2017; Preidel and Borrmann 2016; Sydora and Stroulia 2020), object-oriented methods (Doukari et al. 2022; Garrett Jr and Hakim 1992), logic-based methods (Solihin and Eastman 2016; Tan et al. 2010; Zhang and El-Gohary 2016) and semantic and ontology-based methods (Beach et al. 2015; Hjelseth and Nisbet 2011; Macit İlal and Günaydın 2017; Wu et al. 2021; Zheng et al. 2022; Zhou et al. 2022). The systems have shown many benefits of ACC, including improving the efficiency and accuracy of the compliance checking (Beach et al. 2020; Shahi et al. 2019).

Despite promising results, most of the existing ACC systems can only check quantitative or objective requirements, e.g., numerical requirements or specified properties (Dimyadi et al. 2016; Soliman-Junior et al. 2020). As pointed out by Nawari (2020), none of the current systems can deal with ambiguous and subjective requirements, which are defined as requirements with terms such as “approximately” and “close to”. Other researchers have also identified this issue. Soliman-Junior et al. (2020) reported subjective requirements in Brazilian (RDC 50) and British (HBN 11-01 and HBN 00-03) healthcare requirements, mainly due to “implicit relationships between elements of healthcare built environment”. Examples of implicit relationships include “adjacent to”, “overlaps”, “arranged with a direct relationship to”, etc. Subjective requirements are regarded as only manually checkable. Their later analysis of HBN 00-01, HBN 11-01 and HBN 00-03 led to the classification of subjectivity, including natural subjectivity and artificial subjectivity (Soliman-Junior et al. 2021). The former means rules with abstract elements, such as “safe and secure”, which designers can only interpret during their decision-making process. The latter results from poorly written requirements, such as “adequate sound insulation”. They argued that the required sound insulation could have been better clarified, as sound is measurable and is objectively defined in a related regulatory document. In addition, a recent study by Zhang et al. (2022) proposed a classification of building rules, where they regard rules related to quality and aesthetics or involve personal values as subjective (e.g., pleasant and welcoming).

Although some previous research has touched on ambiguity and subjectivity in building requirements, during our review we identified that there was a need to re-examine this area of knowledge particularly because there appeared to be more categories of ambiguous rules than previously recognised. For example, “seating area” is ambiguous because there is no direct mapping in the design model. “Toilet” is ambiguous because it can mean the room or the device. Trying to understand these new ambiguous rules, we refer to linguistics literature and find categories of ambiguity proposed by linguists. For example, Berry et al. (2003) ’s classification of ambiguity includes lexical, semantic, syntactic, and pragmatic ambiguity. In addition, although ambiguous, subjective, and vague are often used interchangeably in ACC literature, the distinction has been made among them in linguistics. Ambiguity occurs when a statement has more than one meaning. Vagueness appears when there are borderline cases (e.g., 3 meters distance can be close or not close) (Bach 1998). Subjectivity is defined in the Cambridge dictionary as: “the influence of personal beliefs or feelings, rather than facts.” In other words, subjectivity results from personal interpretations of ambiguity or vagueness. A more comprehensive literature review of ambiguity and related concepts can be found in the “Literature analysis” section.

53% of building requirements cannot be checked automatically through ACC, primarily due to ambiguity (Soliman-Junior et al. 2021). The initial findings led to our realisation that we still need to learn more about ambiguity in building requirements, such as the classifications and solutions. Addressing ambiguity could significantly improve the feasibility and efficiency of ACC. We aim to establish a taxonomy of ambiguity in building requirements by unpacking the characteristics of the ambiguity variations in this paper. We explored the strategies for resolving the ambiguity of building requirements in a separate paper.

Methodology

An inductive approach (Birks and Mills 2015) was adopted to establish the taxonomy of the ambiguity in building requirements. The approach aims to produce a substantive theory grounded in the data and fits in the real-world (Gregory 2011). Because there is currently little knowledge of the ambiguity of building requirements, the approach helps better understand and explain the phenomenon (Chun Tie et al. 2019; Gregory 2011). It has also been successfully used in other research in the AEC domain (Hall et al. 2018; Sun et al. 2022; Zhou et al. 2015).

The research method proposed by Birks and Mills (2015) is an iterative process where different steps interplay with each other. The first step is purposive sampling, where data (i.e., building requirements that were analysed in previous research) is purposively selected to help answer the research question. Data collection and analysis were conducted concurrently. The authors collected, coded, and analysed data before more data was collected. Importantly, apart from building requirements, existing literature and prior knowledge related to ambiguity in building requirements and other substantive areas were also included in the dataset to provide better theoretical abstraction, keep the theoretical sensitivity, and understand the contribution to the knowledge (Gregory 2011) , which are shown in Fig. 1.

Coding is an analytical process that includes initial, intermediate, and advanced coding. In the initial coding, the authors tried to find similarities and differences in the ambiguous building rules. For example, words that often lead to ambiguity were identified (e.g., adequate). Initial coding also helped to identify further data collection directions. Following these directions, theoretical sampling was conducted to collect more regulatory documents that provide relevant information. Built on initial coding, intermediate coding transformed initial data into more abstract concepts and selected core categories for the theory to emerge. The data collection and analysis were finished when theoretical saturation was achieved - no new findings can be generated when collecting and analysing new data (i.e., new requirement documents). The advanced coding process helped achieve higher levels of abstraction of the concepts and categories of ambiguity. The authors have practised the storyline technique and theoretical coding to facilitate the theoretical integration and cumulation of the concepts and categories of ambiguity.

Constant comparative analysis was conducted throughout the data collection and coding process to compare codes and develop ambiguity categories iteratively. As a result, concepts and categories of ambiguity were refined. In addition, throughout the whole inductive analysis, memos were written to record the authors' thoughts, feelings, and decision-making. It is also essential to help ensure the rigour and quality of the result. Theoretical sensitivity also encompasses the whole process. Related literature in linguistics, knowledge, software requirement engineering and ACC helped the authors maintain theoretical sensitivity and identify what data is vital for generating concepts, categories, and theory. At the end of these iterative processes, a taxonomy of the ambiguity that is grounded in the building requirements was developed.

Data collection and analysis

This research collected both building requirements and related literature. The inclusion of related literature helped abstract the identified categories and maintained theoretical sensitivity. The data collection and analysis were concurrent and iterative in this study. This section presents the two main iterations of this research. The first iteration includes the analysis of requirements and related literature, and the identification of new categories. The second iteration is both an iteration to find new categories and validation of the identified categories in iteration 1. Details of the iterations (Fig. 2) are explained in the following subsections. The double arrow in Fig. 2 means the data collection and analysis were conducted concurrently.

Iteration 1

In this study, the first step is purposive sampling. The authors purposively collected Health Building Notes (HBN) 00-01, HBN 00-03 and HBN 11-01 (Department of Health and Social Care 2021) for analysis because they are mentioned by previous studies as having ambiguous clauses (Soliman-Junior et al. 2021). The authors reviewed all clauses in the three regulatory documents and followed the coding, memoing, comparative analysis and theoretical sampling processes to identify, refine and abstract these categories.

Building requirement analysis

In the first iteration, the authors' analysis of HBN documents (HBN 00-01, HBN 00-03 and HBN 11-01) found four categories of ambiguity, where one category is new. Example rules (Rules 1-7) from these documents are presented in Table 1.

The first category refers to requirements with abstract elements that can only be interpreted by experts, which is also identified by Soliman-Junior et al. (2021). One example can be found in Rule 1. The interpretation of "pleasant and welcoming" depends on the designers' personal values. Rule 2 is for designing relatives' overnight stay rooms. It also includes abstract information (i.e., it should be able to accommodate). It does not explicitly specify what type of furniture or what size of beds are needed to achieve compliance. Designers have the flexibility if the room can accommodate two people.

The second category refers to poorly written requirements (Soliman-Junior et al. 2021). For example, "adequate space" in Rule 3 is poorly written and results in ambiguity, as the space for furniture, wheelchairs and a bed can be clearly and objectively defined.

The third category is requirements that have implicit relationships between objects or spaces (Soliman-Junior et al. 2020). In Rule 4, "close to" is an implicit relationship because it cannot be directly found in the design model. Similarly, in Rule 5, “visible” is implicit because no corresponding relationship will be modelled in the design. It may have multiple interpretations as the viewpoint “outside the building” is not specified. Whether or not the design meets the requirement depends on which viewpoints the designer selects during interpretation.

The fourth category has not been identified previously. It is for requirements that have objects such as spaces with no direct mapping to the design model. For example, the design model has no corresponding representation of a “touchdown base” (Rule 6) and a “seating area” (Rule 7). They also only include partial or no physical boundaries. When checking these spaces, different interpretations of the boundary of these spaces are possible.

Literature analysis

During the first iteration, we also included the analysis of related literature to see if more categories of ambiguity can be found or if better abstraction can be achieved inspired by previous literature. The following sections present the literature review.

Ambiguity in natural language

Ambiguity is regarded as an intrinsic feature of natural language. A widely accepted definition of ambiguity is that a statement has more than one meaning. One of the earliest work on ambiguity is Empson’s book, which proposed seven types of ambiguity for literature evaluation and criticism (Empson 1962). However, this work mainly focused on how to use ambiguity coherently to improve the readers’ appreciation of the literature, which is not the focus of this research.

Many linguists and philosophers also studied ambiguity. Bach (1998) proposed two types of ambiguity: lexical and structural. Lexical ambiguity happens when a word has more than one meaning (e.g., bank, call), whereas structural ambiguity occurs when a phrase or a sentence has more than one structure (e.g., tall men and women). Structural ambiguity is also known as syntactic ambiguity. Adding two more types of ambiguity, Berry et al. (2003) proposed a classification of ambiguity including lexical, semantic, syntactic and pragmatic ambiguity. The meanings of lexical and syntactic ambiguity are the same as Bach’s work.

Semantic ambiguity refers to ambiguity with the logic form (e.g., the ambiguity of quantifiers and negations in predicate logic). The last category, pragmatic ambiguity, means that the statement has several meanings considering the context. Compared with Bach's work, their classification is with finer granularity (i.e., more sub-classes). For example, lexical ambiguity includes homonymy and polysemy. The former is about two words having the same written and phonetic representation but unrelated meanings (e.g., bank). And the latter occurs when many words have related meanings and the same etymology (e.g., green).

Among ambiguity studies, many stressed the distinction between vagueness and ambiguity (Bach 1998; Berry et al. 2003; Sennet 2011). Vagueness is closely related to ambiguity. It appears if there are borderline cases in a statement (Bach 1998). Words such as "tall" and "long" are typical examples of vagueness, as they apply to a fuzzy instead of a fixed scale (e.g., tall can be more than 1.8 or 1.9 metres).

Subjectivity is also sometimes confused with ambiguity and vagueness. The Cambridge dictionary defines it as "the influence of personal beliefs or feelings, rather than facts." Different from vagueness and ambiguity being properties of natural language, subjectivity results from human's interpretation of vagueness and ambiguity. This is because, during interpretation, the disambiguation may be affected by personal beliefs or feelings.

Ambiguity in legal language

According to Cao (2009), there are mainly four types of legal language, including legislative language (e.g., treaties, laws), judicial language, scholarly language (e.g., in academic work or commentaries) and other legal language used in private legal documents such as contracts and leases. Previous studies have explored the vagueness and ambiguity in different types of legal language using manual or automatic methods. Li (2017) conducted a corpus-based study to detect and classify vague terms in legislative texts. The results showed four semantic groups of vague terms, including quantity (e.g., some), time (e.g., sometimes), degree (e.g., adequate) and category (e.g., such measures). More recently, some semi-automatic methods have been proposed to detect vagueness in construction contracts. For example, Candaş and

Tokdemir (2022) developed a method to detect vagueness in FIDIC contract conditions using natural language processing (NLP) and machine learning sequentially. They compared the detection performance of the supervised machine learning approach and the rule-based approach, where they found that the latter achieved higher accuracy.

Despite the methods of identifying vagueness, the above-mentioned research has not analysed ambiguity in legal language. Reidenberg et al. (2016) used grounded theory to develop a theory of vague and ambiguous terms in website privacy policies. They proposed a four-category taxonomy of vague terms, namely condition (e.g., depending), generalisation (e.g., generally), modality (e.g., modal verbs) and numeric quantifier (e.g., some). Apart from vague terms, they also identified incompleteness as another source of ambiguity because incompleteness of information may lead to different interpretations and understandings. Massey et al. (2014) analysed regulations for software engineering and developed a taxonomy of ambiguity incorporating legal, software engineering and linguistic understandings of ambiguity. The taxonomy includes lexical, syntactic, semantic, vagueness, incompleteness and referential ambiguity. In their later work, they presented an ambiguity intensity map in legal texts as a guide for experts to spot ambiguity quickly (Massey et al. 2015).

Ambiguity in requirements engineering

Ambiguity is extensively studied in the software requirements engineering (RE) domain. In software engineering, RE requires a concise, clear and consistent requirements document describing the system's functional and non-functional properties (Kamsties and Peach 2000). Requirements can be documented using natural or requirement specification languages, such as UML (Unified Modelling Language). However, requirements written in natural language are often ambiguous. The ambiguity may lead to software failures and a waste of time (Yadav et al. 2021). Using formal requirement specification languages can rarely deal with ambiguity well, often resulting in misunderstandings being documented in the unambiguous requirements (Kamsties et al. 2001). To address this issue, many studies have been conducted to detect and address the ambiguity.

Some research developed manual approaches for identifying ambiguous words in software requirements specifications. For example, Kamsties and Peach (2000) identified two types of ambiguity, namely linguistic and RE-specific ambiguity. Some examples of the former ambiguity are ambiguous noun references or semantic meanings. The latter pertains to the application domain or system domain. They proposed a checklist to identify linguistic ambiguity and four heuristics to detect and document RE-specific ambiguity in a UML metamodel. Gervasi and Zowghi (2010) analysed the sources of ambiguity related to linguistics on lexical, syntactical and semantic levels. Based on whether or not the ambiguity is recognised by the writer, they divided ambiguity into intentional and not intentional categories. Berry (2007) and Berry and Kamsties (2004) provided a more comprehensive taxonomy of requirements ambiguity, including four aspects: vagueness, generality, linguistic and software engineering (SE) ambiguity. Linguistic ambiguity includes lexical, syntactic, semantic, pragmatic, and language error ambiguity. SE ambiguity includes requirement documents ambiguity, application domain ambiguity, system domain ambiguity and development domain ambiguity. These types of ambiguity were further explained using examples.

More recently, some studies used semi-automatic or automatic approaches to detect, measure and reduce ambiguity. For example, Matsuoka and Lepage (2011) developed a checker using semantic similarity in WordNet, inverse document frequency and C-Value to identify possibly ambiguous words in software requirement specifications. The test experiment showed that two-thirds of terms were regarded as ambiguous. Many solutions were realised using Natural Language Processing (NLP). Ferrari and Gnesi (2012) proposed an algorithm to detect pragmatic ambiguity. They compare the concepts in requirement sentences and the corresponding concept paths in each knowledge graph extracted from domain-knowledge documents. The requirement sentences are ambiguous if they have two or more similar concept paths. Popescu et al. (2007) developed a semi-automatic method to identify and reduce ambiguity in software requirement specifications based on object-oriented models. Nigam et al. (2012) developed a tool based on NLP to help detect lexical, syntactic and syntax ambiguity. Osborne and MacNish (1996) demonstrated how NLP could be used to reduce the ambiguity of software requirement specifications by representing them using formal representations. Huertas et al (2011) proposed a formal approach to measuring written lexical ambiguity in natural language requirement specifications. Importantly, they not only focused on the text's ambiguity but stressed stakeholders' knowledge factor. When stakeholders share the same knowledge, ambiguous text may be in practice unambiguous, as it only has one meaning among stakeholders.

Similar to Huertas et al (2011), some other studies also recognised the linkages between knowledge and ambiguity. Ferrari et al. (2016) found that ambiguity in requirement elicitation interviews is a powerful source of identifying tacit knowledge. In other words, some ambiguity is caused by tacit knowledge. Gervasi et al. (2013) unpacked tacit knowledge in requirement engineering. They reviewed literature on tacit knowledge, including Polanyi (2009)'s distinction between tacit and explicit knowledge and Collins (2010)'s classification of tacit knowledge. Recognising Collins' classification is not suitable for identifying ambiguity in RE, they proposed a framework for understanding tacit knowledge in the RE domain and defined properties that characterise the environment where tacit knowledge emerges.

Some academics attempted to make the tacit knowledge explicit. Friedrich and Van Der Poll (2007) included developers in the client's business environment to better understand domain knowledge and satisfy client's needs. Gacitúa et al. (2009) provided techniques to help understand the impact of tacit knowledge and improve requirements quality to alleviate the negative effects of tacit knowledge. Nevertheless, using these methods, they offered no guarantee that tacit knowledge can be detected and made explicit.

Ambiguity and subjectivity in building requirements

In the ACC domain, only few papers shed light on ambiguity and/or subjectivity. Some research focused on understanding the subjectivity and ambiguity of building requirements by providing classification or taxonomy. In the taxonomy of building requirements proposed by Soliman-Junior et al.

(2020), requirements were categorised into quantitative, qualitative and ambiguous based on their nature. Ambiguous requirements mean that it is hard to tell whether they are quantitative or qualitative in nature. In their later research, Soliman-Junior et al. (2021) identified two types of subjectivity in healthcare requirements: natural and artificial subjectivity. Rules with natural subjectivity involve some abstract elements (e.g., design flexibility). These abstract elements need human involvement to be interpreted into tangible and executable requirements. Artificial subjectivity is often the result of poorly-written requirements. They suggested that the elimination of such subjectivity can be done by using objective, clear and precise sentences. In his four-category classification of building clauses, Nawari (2020) also identified ambiguous requirements as subjective clauses that include unclear words or phrases. Zhang et al. (2022) proposed a classification of building rules, where they regard rules related to quality and aesthetics or involve personal values as subjective. Although these studies identified some types of subjectivity and presented some examples, no in-depth analysis of ambiguity or subjectivity was provided.

Other research proposed solutions to address ambiguity and subjectivity in building requirements. For example, Soliman-Junior et al. (2020) provided some examples of subjective rules related to spatial relationships. They suggested using semantic enrichment to address the subjectivity of adjacency and containment rules but neither the detailed method nor the validation was provided. Another work by them interviewed designers to understand their perspectives on using automatic tools to assist compliance checking (Soliman-Junior et al. 2022). The findings show that designers believe that subjectivity is not to be eliminated but needs to be managed to maintain design creativity. Suggestions were proposed by designers on how to address subjectivity, including using a large dataset to support design decision-making and better drafting the regulations. However, this research only interviewed designers; thus, the suggestions are only from the designer's perspective regarding how the requirements could be changed so as to make it easier for designers to comply. There was no analysis of the reasons for subjectivity with no attempt to systematically address the problem.. Hjelseth (2013) attempted to address ambiguity in regulations using the Test Indicator Objectives (TIO) method. This method converted ambiguous rules into computable quantitative metrics. Such a method has been prevalently used in commercial software such as Solibri (Solibri 2022). However, as pointed out by Li et al. (2020), these "magic numbers" may not be based on sufficient evidence and are neither transparent nor traceable. They instead used spatial artefacts to address several cases of ambiguity related to spatial rules, such as regulations related to accessibility, visibility and functional spaces.

Refinement of the results from the first iteration

The above literature review provided some inspirations that may be helpful for the identification and abstraction of ambiguity in building requirements. Firstly, regarding linguistics, so far, only "poor use of language" has been identified in building requirements. As building requirements are written in natural language, other types such as lexical, semantic, syntactic and pragmatic ambiguity may also apply to building requirements. Secondly, building requirements are a type of legal text, the types of ambiguity identified in legal studies may also apply to building requirements, such as vagueness and incompleteness. Thirdly, tacit knowledge can lead to ambiguity. Fourthly, similar to RE-specific ambiguity, there may also be ambiguity types specific to the application and system domains of building requirements and ACC. Some more example rules (Rules 8-22) are presented in Table 2.

The literature analysis helped us find another category of ambiguity in HBN 00-03, namely ambiguity caused by tacit knowledge. For example, Rule 8 seems to indicate that there should be a circulation route between the information/resource centre and the beverage-making facilities. However, regulators may think that "with access to" also means the door should be wide enough for wheelchair users to pass. Readers may not find "with access to" ambiguous because they have done unconscious disambiguation when first reading the clause (Berry et al. 2003). The design assumptions have been made by the reader without them knowing the tacit knowledge related to accessibility.

In addition, after careful review and analysis, the authors found that Rule 1 and Rule 2 belong to tacit knowledge and intentional ambiguity, respectively. While the regulators strived to write unambiguous requirements, they could not do so for Rule 1. This is because the criteria of "pleasant and welcoming" relate to social and psychological knowledge that can hardly be explained explicitly. Further details of tacit knowledge can be found in the "Tacit knowledge" section. By contrast, the ambiguity in Rule 2 is introduced intentionally to promote design flexibility, because it is possible to specify requirements for furniture, room area and bed size etc, but the regulators chose not to do so.

Iteration 2

In the second iteration, three more requirement documents were selected: HBN 00-02, 00-04 and 04-01(Department of Health and Social Care 2021). They were selected because firstly, the drafting of HBN is to a lower standard than regulatory documents such as Approved Documents, so they are more likely to be ambiguous; and secondly, they focus on the design stage rather than the operational stage, so there is more need to resolve ambiguity before the construction stage. The authors first used HBN 00-02 to validate the results from the first iteration and to see if new findings can be found. Like the first iteration, coding, memoing, comparative analysis and theoretical sampling were performed. In addition to previously identified ambiguity categories, three new categories were found, including lexical ambiguity, incompleteness, and one-to-many mapping in the building design.

An example of lexical ambiguity is "WC". The lexical ambiguity occurs because the word "WC" has more than one meaning (i.e., the room or the device), and it is hard to tell which meaning is intended.

Incompleteness means that the information provided in the clause is insufficient for the domain experts to provide one unambiguous interpretation. For example, because the term "special bath" in Rule 9 is not explicitly defined in the requirements, many dimensions or types of baths can be considered special.

Rule 10 is an example of one-to-many mapping to building design. "Hand-rinse or personal washing facilities" can include multiple types of basins, including wash-hand basins, hand-rinse basins and clinical wash-hand basins, which are defined differently. Thus, "hand-rinse or personal washing facilities" may be interpreted differently and can lead to ambiguity.

At the end of the second iteration, the analysis of HBN 04-01, HBN 00-04 did not generate new findings. Thus, theoretical data saturation is achieved, and advanced coding is performed. The advanced coding process helped achieve better theoretical abstraction of the identified categories. For example, some categories mentioned above are merged or become sub-categories of main categories. The final taxonomy was generated using these new categories, as presented in the next section.

Results

The taxonomy is presented in this section. The authors found two primary categories for ambiguity, namely intentional ambiguity and unintentional ambiguity. Three main categories of unintentional ambiguity were identified, including ambiguity related to the use of language, tacit knowledge and ACC-specific issues. The taxonomy of ambiguity is summarised in Fig. 3 and further developed in the following sections.

Intentional ambiguity

The analysis of building requirements showed some intentional ambiguity. Intentional ambiguity refers to ambiguous rules that can be made unambiguous, but the regulators chose to include certain level of ambiguity for some purposes, such as promoting design flexibility (Soliman-Junior et al. 2021) and maintaining validity against technological changes (Morgan 1999). Intentional ambiguity has been identified and explained in previous research. For example, Otto and Antón (2007) suggested that some ambiguity accurately reflects the regulator's intent; they are created to let inspectors determine compliance in later stages, such as in the case of appeal or in courts. Although there is no explicit indication that those ambiguous rules are intentional in current building requirements, this intention can be inferred from the shift from prescriptive rules to performance-based rules in the UK building regulatory documents. For example, before 1985, building requirements in the UK provided detailed instructions for compliance and no deviation was allowed (Morgan 1999). Despite the advantages of ensuring clarity and alleviating corruption approval, this prescriptive approach discouraged innovation and made it hard to adapt to technological advances. Recognising these issues, in 1985, a new regulating method for fire safety was adopted in the UK. The new approach is performance-based. It has simpler requirements with deliberate oversimplification, where no details were given on how to achieve compliance.

These intentionally ambiguous requirements are mostly performance-based. They are to support the decision-making of the design without overly constraining it. Paths for compliance were not specified to achieve better design flexibility and innovation. An example of such intentionally ambiguous rules can be found in Rule 11. There is no strict restriction on the floor's slope or the gully's location. It allows different combinations of the gully location and floor slope; therefore, better design flexibility is achieved.

Unintentional ambiguity

Despite some intentional ambiguity in requirements, most ambiguity is unintentional. The unintentionally ambiguous requirements can be categorised into three main classes. The following subsections will further explain the three classes. Note that these types of ambiguity are not mutually exclusive for each rule provision and can co-exist.

The use of natural language

The first class of ambiguity pertains to the use of natural language. Rules are written in natural language; and ambiguity is an inherent feature of natural language. As mentioned in the "Ambiguity in natural language" section, there are many sub-classes of linguistics ambiguity, many of which have been found in building requirements, which will be further explained in this section. The term linguistic ambiguity is not used here because while vagueness and incompleteness are related to the use of natural language, they do not belong to linguistic ambiguity.

Vagueness

Vagueness often results from poor or sloppy use of language. In building requirements, it typically appears in insufficiently defined words or phrases, often including adjectives or adverbs (e.g., long enough, sufficient). For example, Rule 12 is a requirement for the length of the shower hose. The vagueness occurs because the use of "long enough" is sloppy. "Long enough" has a fuzzy scale, leading to borderline cases (e.g., 3 metres can be long or not long at the same time). Notably, "long enough" is considered as a poor use of language instead of design flexibility because it should be possible to have a minimum length requirement or a length range for the shower hose, given that the length of the patient shower trolly is known.

While Rule 12 presents vagueness in object property, Rule 13 is an example of vagueness in space. In Rule 13, it is hard to know what is "sufficient space". This vagueness can be easily avoided as it is clear that the space is for the mobile hoist. The required dimensions or area can be specified by considering the typical dimensions of mobile hoists.

Incompleteness

Incompleteness refers to cases when there is missing information in the rule provision. Because of the missing information, there is more than one possible interpretation of the rule provision. Depending on what information is missing, incompleteness can lead to negative results such as ill-defined responsibility (Rule 14) or failure to identify non-compliance (Rule 9).

In Rule 14, it is unclear who should be responsible for the position of the adjustable tip-up shower seat. It poses problems for compliance checking as it is unclear at what stage (i.e., design or operation) this rule needs to be checked.

In Rule 9, "special" does not provide necessary information regarding what baths are special. There is also no definition of "special bath" provided in the context of this rule. Designers can thus have different interpretations. For example, a special bath can be interpreted as any bath that does not have the dimensions as illustrated in the graphics in the regulatory documents. A special bath can also be a bath that has dimensions exceeding certain values based on the designer's experience. The varied interpretations may lead to non-compliance. When designers include a special bath in the design, they may not be aware that it is regarded as a special bath by regulators and inspectors. Consequently, they may not know additional space is required and the design is not compliant with requirements.

Lexical ambiguity

Lexical ambiguity is caused by a word or phrase having multiple meanings. A sentence is ambiguous when these meanings are all plausible and the reader cannot tell which meaning is intended by the regulator. In building requirements, examples of words with multiple meanings are "WC" and "toilet". According to the Cambridge dictionary, WC refers to a toilet or a room containing a toilet. Toilet also has two meanings. It refers to either "a device into which people excrete waste" or "a room with a toilet in it". To make the problem worse, in building requirements, WC and toilet are often used interchangeably, making it harder to understand the intended meaning. For example, Rule 15 and Rule 16 are from BS8300 (British Standards Institution 2018) and HBN 00-02, respectively. It can be inferred from the context that in the example from BS8300, toilets are rooms. However, in the example from HBN 00-02, WCs are rooms and toilets are devices.

Tacit knowledge

As mentioned in "Ambiguity in requirements engineering" section, research by Ferrari et al. (2016) reported that some ambiguity in software requirements is due to tacit knowledge. Similarly, our analysis found that tacit knowledge is also a type of ambiguity in building requirements. Building requirements are written to summarise and convey engineering and construction knowledge. With careful writing, explicit engineering and construction knowledge can be presented unambiguously. However, apart from that, a large amount of tacit knowledge cannot be easily formalised, aggregated or written down. In this paper, we adopted the three categories proposed by Collins (2010) to help identify ambiguity resulting from tacit knowledge embedded in building requirements. The three categories are relational tacit knowledge (RTK), somatic tacit knowledge (STK) and collective tacit knowledge (CTK). In Collins (2010), RTK is about how people relate to each other; STK is related to physical things of people's brains and bodies, such as bike balancing; and CTK has to do with the nature of society. Because no building requirements focus on physical activity, only relational tacitness and collective tacitness are found to be related to ambiguous building requirements.

Relational tacit knowledge

Relational tacit knowledge pertains to the contingencies of relationships among people, human history and tradition (Collins 2010). In the case of building requirements, relational tacit knowledge is due to the contingencies of relationships between regulators and designers. The ambiguity in requirements can arise from the relative possession of knowledge by regulators and designers, where regulators typically possess more knowledge than designers. The possession of knowledge also varies among designers, as designers have different previous experiences and training.

Taking an accessibility rule as an example (Rule 17), some designers think the word "accessible" is unambiguous, while others believe it can have several interpretations. In ACC literature, researchers have interpreted "accessible" as different things. Jiang et al. (2022) believe that the term accessible means the two spaces share the same door. Li et al. (2020) developed the spatial artefact of accessible spaces, where they believe there are two requirements to be satisfied. Firstly, accessible space is a space that can be reached from another space via circulation routes. Secondly, based on New Zealand regulations, the doors of the accessible spaces need to be at least 0.85m wide for a wheelchair user to pass. According to Collins (2010), when making this rule, the regulator assumed that designers possess some essential pieces of explicable knowledge, such as explicable knowledge about accessibility. Regulators have an idea of what designers know and try only to write down what may not be obvious to them in the requirements to fill the knowledge gap. In other words, regulators might not know that the designers do not know what they mean by accessibility. This is a type of RTK called mismatched saliences (Collins 2010). This type of RTK can be made explicit once the salience of each party has been understood.

Another type of rule with RTK is the adjacency rule. This type of rule often has terms such as "next to" or "adjacent". These terms are ambiguous for two reasons. Firstly, the meaning of these terms is not fixed but depends on the context. Whether the rule checks the relationship between spaces, objects or an object and a space will determine if the adjacency is a matter of metres or centimetres. The terms can also have slightly different meanings depending on the reasons for these requirements (i.e., adjacent objects for ergonomic considerations or fire safety). Secondly, even if designers correctly understand the context, they may still have different interpretations on what should be the exact distance range of these adjacency requirements, potentially due to their varied previous experiences and training. The requirements concealed specific knowledge and can only be understood by designers with some experience. Novice designers may struggle to interpret these rules or misinterpret them. For example, Rule 18 requires that the hand-rinse basin be adjacent to an independent wheelchair toilet. The context for this requirement includes: 1) the adjacency is between two objects within the same space (i.e., bathroom); 2) the reason for having this requirement is the convenient reach by the independent wheelchair user between the use of toilet and hand-rinse basin. While designers may understand the context, different designers can still have different interpretations regarding what distance is adjacent in this case.

According to Collins (2010), RTK can be made explicit. Strategies to make RTK explicit relate to the relative knowledge possessed by people and are out of the scope of this paper.

Collective tacit knowledge

In building requirements, collective tacit knowledge is another type of tacit knowledge leading to ambiguity. CTK can only be understood in a social context, as CTK is in society and is about how society is organised (Collins 2010). Although CTK is hard to be written down, it can be interpreted by domain experts because experts have acquired tacit knowledge through social interactions. In Rule 19, “safe and secure” is a typical example of ambiguity caused by CTK. There are many ways to make this area safe and secure, such as 1) adding a door with a security lock and 2) making it spacious and without obstruction that can hurt children when they are playing. However, measuring if a design meets the "safe" and "secure" requirements is challenging. It is also tricky to make CTK explicit because of its social relevance.

Other examples of ambiguity caused by CTK are aesthetics and quality rules. To illustrate, it may be relatively easy to describe some explicable knowledge of colours, materials and different types of architecture. However, it is hard to express what is aesthetic and what is of good quality, as aesthetics and quality cannot be understood if taken out of the context of society.

According to Collins (2010), collective tacit knowledge is strong tacit knowledge. The resistance to making CTK explicit is the strongest among all tacit knowledge, making it almost impossible. Thus, rules related to quality, aesthetics or other personal value are regarded as non-explicable. As a result, these rules need to be checked manually by experts using their tacit knowledge acquired from society.

ACC-specific ambiguity

Similar to the RE-specific ambiguity in software engineering, there is also ambiguity that arises from the application domain and system domain of automatic compliance checking. Requirements in this category, if taken out of the context of automatic compliance checking, are unambiguous and can be easily understood by humans without possibilities of other interpretations. They only become ambiguous because there is ambiguity in mapping objects/relationships in requirements to objects/relationships in the design model. In other words, having a one-to-one direct mapping between the requirement and design is not always possible. There may be a one-to-many relationship or there may not be a direct representation of the object/relationship mentioned in the requirement in the design model. Amor and Dimyadi (2021) has also pointed out this misalignment. An example of the former case is shown in Rule 20. In this rule, fixtures can be mapped to many objects, such as mirrors, soap dispensers and paper towel dispensers. All these fixtures should not conflict with the height-adjustment mechanism of the basin for this rule to pass.

A typical example of the latter case is functional space. This is because 1) the semantic information in the requirements is richer than in the BIM model, and 2) the required space function information is typically not modelled in the target design such as a BIM model. Thus, there is no direct mapping between the requirement and the design. For example, in Rule 21, although experts can easily understand what is a touchdown base by looking at the requirements, there is no direct mapping between the touchdown base and its representation in the design model. Adding to the problem is that the touchdown base and many other functional spaces (e.g., seating area) only have partial physical boundaries or do not have a physical boundary. As a result, there is ambiguity because there can be multiple interpretations of the boundaries (physical or virtual) of the touchdown base.

Some other examples of the latter case are visibility rules. In Rule 22, patients and staff will not be modelled in the design. As "line of sight" is an abstract and virtual concept, there is also no representation in the design of the line of sight between the patient and the staff member. Also, both patients and staff can move, and there are multiple possibilities for the sightlines. There is no direct mapping of the object or the relationship to be checked in the design model. This rule is thus ambiguous because there could be many possible interpretations of it.

Discussion

This study developed a taxonomy of ambiguity in building rules. The results show that there is intentional and unintentional ambiguity, with three main categories for unintentional ambiguity: the use of natural language, tacit knowledge and ACC-specific. Seven sub-categories of ambiguity were also identified: incompleteness, vagueness, lexical ambiguity, RTK, CTK, one-to-many mappings to design and no direct mapping to design. Compared with previous research (Soliman-Junior et al. 2020; Soliman-Junior et al. 2021), this study discovered more ambiguity categories and provides finer granularity for them. Two more categories and six more sub-categories of unintentional ambiguity were found in this study. While previous research has attributed ambiguity mainly to the use of language, results from this study showed that many cases of ambiguity are due to tacit knowledge and problems mapping to the design model. As for intentional ambiguity, instead of regarding abstract elements such as "safe and secure" as intentional ambiguous, this paper pointed out that they are unintentional ambiguity resulting from CTK.

This paper is the first to point out that in building requirements, some types of ambiguity lie in the context instead of words or phrases in the requirement. In this paper, two types of such contexts have been found. Firstly, the interpretation of some requirements is dependent of the several sentences above and/or below and the purpose of the requirement. For example, as mentioned in the "Tacit knowledge" section, the interpretation of adjacency requirements is related to both the subjects and objects in the requirement (i.e., the adjacency of two rooms or two chairs) and the reasons for having this requirement (e.g., for accessibility or fire safety, which may be found in section titles). Secondly, ambiguity in building requirements may arise under the automated compliance checking context. In other words, some building requirements may not seem ambiguous in themselves. However, when considering their alignment with the target design model, there may be mapping issues such as no direct mapping and one-to-many mapping to design. These lead to multiple interpretations, thereby making the requirements ambiguous.

Conclusion

Previously, ambiguity in building requirements has neither been thoroughly analysed nor addressed in current ACC systems. This significantly impedes the productivity improvement of using ACC systems. In this paper, the authors adopt an inductive approach to develop a taxonomy of ambiguity in building requirements.

This study contributes to the body of knowledge in two ways. Firstly, this paper is the first study to systematically explore and categorise ambiguity in building requirements. This research is the most comprehensive on the ambiguity of building requirements, where the most types of ambiguity are identified and explained. The proposed taxonomy could serve as a checklist to help domain experts to identify ambiguity in building requirements during rule interpretation. Secondly, this is the first ACC research to understand the ambiguity of building requirements with considerations of related domains. It has a sound theoretical base in linguistics, knowledge, requirement engineering and code compliance checking.

This research opens up opportunities for addressing ambiguity in building requirements and expanding the percentage of requirements to be checked automatically in future ACC system. Solutions can be proposed based on the types of ambiguity instead of using arbitrary quantitative metrics, which are expected to be more suitable to address each type of ambiguity.

This research has some specific limitations. This research mainly aims to better explain the ambiguity issue in building requirements. As the proposed classification is grounded in the collected data, it does not guarantee generalisation in other requirements. More types of ambiguity may be found when analysing more building requirements. In future research, we will continue to investigate ambiguity issues, understand which type of ambiguity is the most and least amenable to resolution and suitable approaches.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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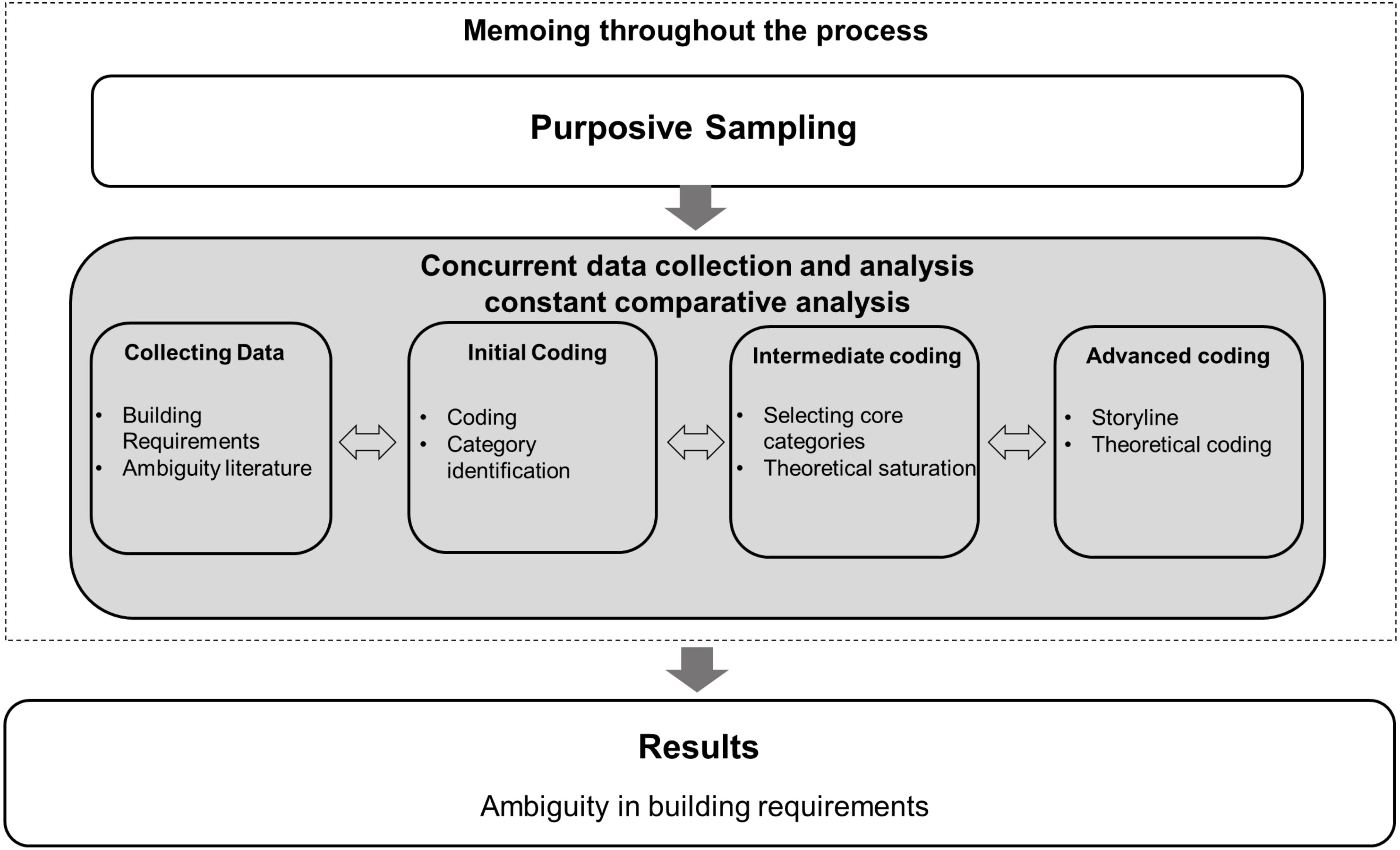
Table 1. Example building requirements with ambiguity in iteration 1

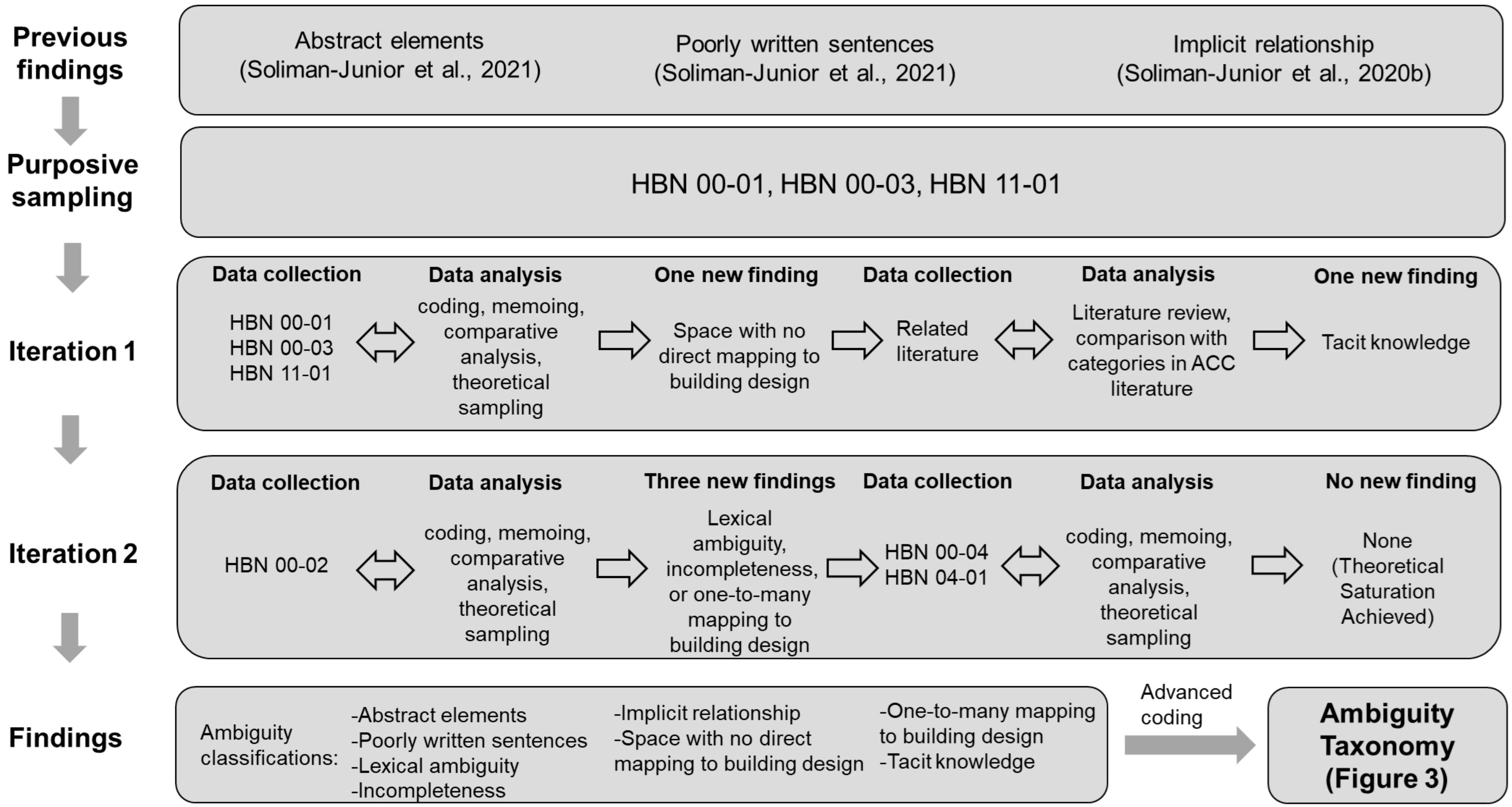
No.	Documents	Example Rules
Rule 1	HBN 00-01	Appendix 1. The main entrances and reception areas should be pleasant and welcoming.
Rule 2	HBN 00-03	11.24 This room is for sleeping only. It should be able to accommodate two people.
Rule 3	HBN 00-03	2.3 …There should be adequate space for moveable furniture and unobstructed access for wheelchairs, as well as space to accommodate overnight visitors.
Rule 4	HBN 00-03	7.23 Waiting areas should be close to the clinical or work area served and WC facilities.
Rule 5	HBN 11-01	6.1 The public zone, made up of the main entrance, reception and associated spaces, should be: …visible from outside the building, to aid building legibility.

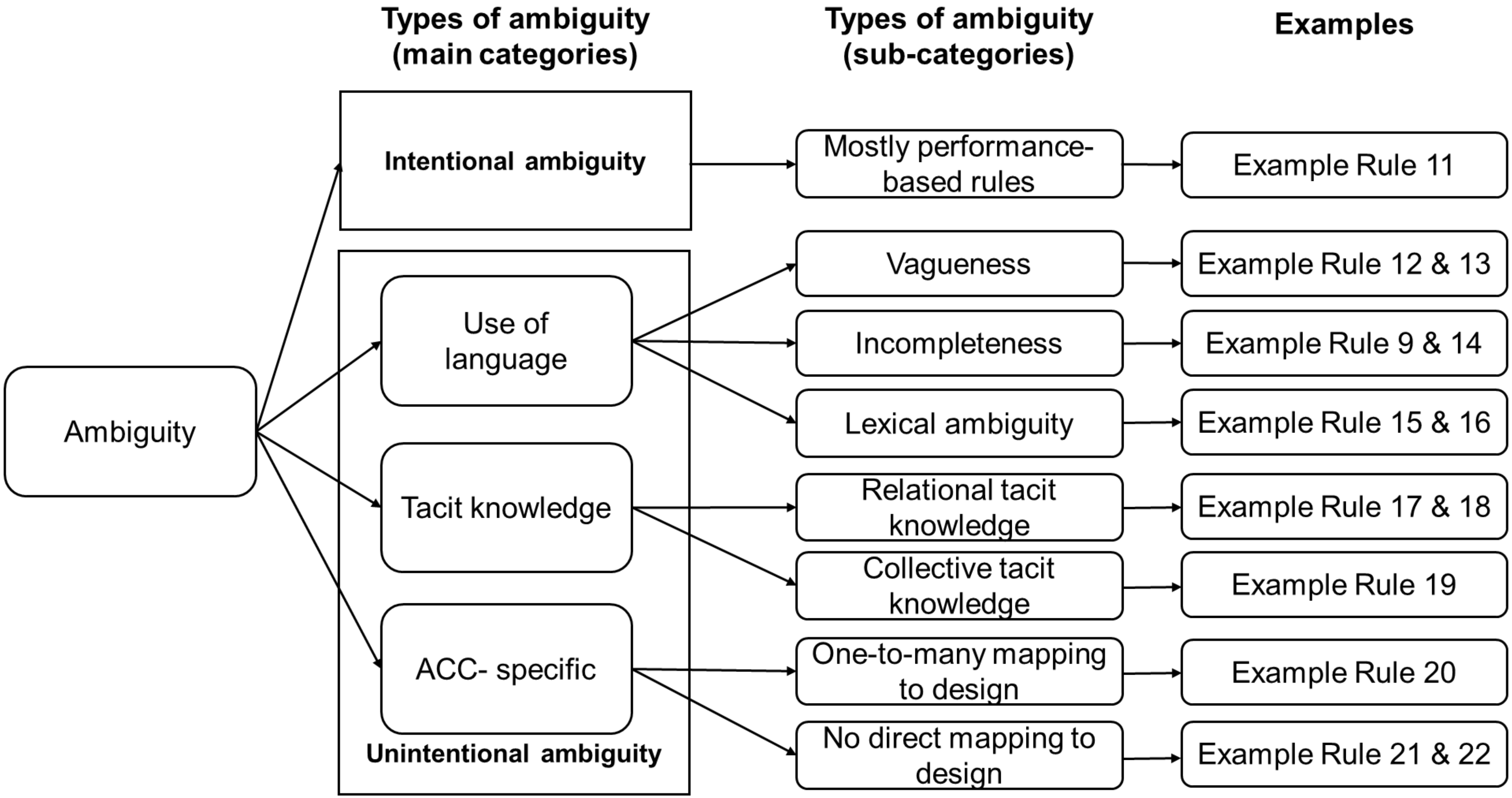
Rule 6	HBN 00-03	12.70 The touchdown base may consist of a worktop (as shown) or mobile workstation and computer at standing height.
Rule 7	HBN 00-03	14.19 An identical space provision is suitable for semiambulant users though it should be located adjacent to a seating area.

Table 2. Example building requirements with ambiguity in refinement of iteration 1 and iteration 2

No.	Documents	Example Rules
Rule 8	HBN 00-03	7.15 Information/resource centre should be located close to an entrance or waiting area with access to beverage-making facilities.
Rule 9	HBN 00-02	2.41 Additional space may be required for special baths.
Rule 10	HBN 00-02	3.8 Hand-rinse or personal washing facilities should be provided either within the associated WCs or immediately outside them, accessible from the changing area.
Rule 11	HBN 00-02	4.50 The shower rooms are assumed to be wet rooms. The slope of the floor and location of the floor gully should ensure that water does not escape into the adjoining bedroom.
Rule 12	HBN 00-02	4.103…The shower hose should be long enough to allow staff to shower the full length of the patient from either side with a trigger handle…
Rule 13	HBN 04-01	4.57 If mobile hoists are to be used, design teams should ensure that there is sufficient space within the ward to store them. Other devices for transferring patients will also need to be stored.
Rule 14	HBN 00-02	4.48 The room layout includes an adjustable tip-up shower seat. This is to allow for both non-assisted and assisted showering. The position of the shower seat should be adjusted between uses as required.
Rule 15	BS 8300	18.1.2 Where only one bathroom, shower room, changing room or toilet can be provided, it should be a unisex type, preferably designed for right‑ hand transfer (see examples in 18.5.3.1).
Rule 16	HBN 00-02	5.48 The following activities take place in a semi-ambulant WC (see Figure 88): use of the toilet…
Rule 17	HBN 00-02	3.8 Hand-rinse or personal washing facilities should be provided either within the associated WCs or immediately outside them, accessible from the changing area.
Rule 18	HBN 00-02	2.36 Bathrooms for independent wheelchair use should contain an independent wheelchair toilet and adjacent hand-rinse basin, separate wheelchair wash-hand basin for personal washing and an independent wheelchair bath.
Rule 19	HBN 00-03	7.1 A safe and secure children's play area should be provided off all main waiting areas.
Rule 20	HBN 00-02	4.32 The position of the grabrails and fixtures should not conflict with the height-adjustment mechanism of the basin.
Rule 21	HBN 04-01	4.52 There should be a number of touchdown bases throughout the ward, which may be located in a variety of ways…
Rule 22	HBN 04-01	2.8 If patients are to stay in an isolation room, it is important that they are able to see staff from their beds. This reduces the psychological problems of isolation. Staff should also be able to see the patient in case of emergency.


Memoing throughout the process
Purposive Sampling
Concurrent data collection and analysis
constant comparative analysis
Collecting Data
• Building Requirements
• Ambiguity literature
Initial Coding
• Coding
• Category identification
Intermediate coding
• Selecting core categories
• Theoretical saturation
Advanced coding
• Storyline
• Theoretical coding
Results
Ambiguity in building requirements


Previous findings
Abstract elements (Soliman-Junior et al., 2021)
Poorly written sentences (Soliman-Junior et al., 2021)
Implicit relationship (Soliman-Junior et al., 2020b)
Purposive sampling
HBN 00-01, HBN 00-03, HBN 11-01
Iteration 1
Data collection
HBN 00-01
HBN 00-03
HBN 11-01
Data analysis
coding, memoing, comparative analysis, theoretical sampling
One new finding
Space with no direct mapping to building design
Data collection
Related literature
Data analysis
Literature review, comparison with categories in ACC literature
One new finding
Tacit knowledge
Iteration 2
Data collection
HBN 00-02
Data analysis
coding, memoing, comparative analysis, theoretical sampling
Three new findings
Lexical ambiguity, incompleteness, or one-to-many mapping to building design
Data collection
HBN 00-04
HBN 04-01
Data analysis
coding, memoing, comparative analysis, theoretical sampling
No new finding
None (Theoretical Saturation Achieved)
Findings
Ambiguity classifications:
-Abstract elements
-Poorly written sentences
-Lexical ambiguity
-Incompleteness
-Implicit relationship
-Space with no direct mapping to building design
-One-to-many mapping to building design
-Tacit knowledge
Advanced coding
Ambiguity Taxonomy (Figure 3)


Types of ambiguity (main categories)
Types of ambiguity (sub-categories)
Examples
Ambiguity
Intentional ambiguity
Use of language
Tacit knowledge
ACC- specific
Unintentional ambiguity
Mostly performance-based rules
Vagueness
Incompleteness
Lexical ambiguity
Relational tacit knowledge
Collective tacit knowledge
One-to-many mapping to design
No direct mapping to design
Example Rule 11
Example Rule 12 & 13
Example Rule 9 & 14
Example Rule 15 & 16
Example Rule 17 & 18
Example Rule 19
Example Rule 20
Example Rule 21 & 22

List of figure captions

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The authors wish to thank the editors and reviewers for their time in effort in reviewing our manuscript. We hope the changes listed have made the manuscript suitable for publication, and we look forward to your response.

Editor Comments	Authors' Response
The paper is recommended for revise for editor only. Authors are encouraged to fully review the most up-to-date and recent publications (~3 years) from JME on the domain knowledge, methodologies that have been applied, and relevant managerial implications. Thank you. Thank you.	Thank you for your comment. We have reviewed the most up-to-date and recent publications from JME on the domain knowledge, methodologies that have been applied, and relevant managerial implications. We have added the related citations to the paper, such as: Wu, H., Zhong, B., Li, H., Guo, J., and Wang, Y. (2021). "On-Site Construction Quality Inspection Using Blockchain and Smart Contracts." Journal of Management in Engineering, 37(6), 04021065. Jiang, L., and Leicht, R. M. (2015). "Automated Rule-Based Constructability Checking: Case Study of Formwork." Journal of Management in Engineering, 31(1), A4014004. Shahi, K., McCabe, B. Y., and Shahi, A. (2019). "Framework for Automated Model-Based e-Permitting System for Municipal Jurisdictions." J Manage Eng, 35(6).
AE: Please address the minor comments from reviewer #2 and submit the paper for re-review by editors only.	Thank you for your comment. We have carefully reviewed the comments by reviewer 2 and made a thorough revision to the manuscript. A point-to-point response to editor and reviewers' comments is provided in this document.

Reviewer 2's Comments	Authors’ Response
This article has been revised extensively in response to the reviewer comments. The resulting paper reads very smoothly and clearly; and it is very interesting and insightful. The conclusions are very clear. So, for me, this article is entirely ready for publication. I marked the paper acceptable as is, yet suggest the authors to: - check carefully for language during the proofreading phase (even though language already is very high quality). As one example, in several cases, I lack the word 'that' which is often left out in spoken language, yet is typically included in academic written language. See line 299-300 for two such examples. Other lines that I marked are: 55, 259, 280, 314-315.	Thanks for your comment. We have carefully checked and proofread the language in this manuscript and made the following changes: We have added “that” to line 260, Line 300 and Line 302. We have also polished the language in Line 55-57, Line 280-282, and Line 315-318, Line 519 and Line 553 to make them clearer.
- I would consider to merge the discussion and conclusion. There is quite some duplication there that is not needed. One clear conclusion seems sufficient to me. The rest of the paper already has a lot of (useful) discussion.	Thank you for pointing this out. We have deleted the repetitive content in the conclusion section (i.e., the content repeating the specific categories in the taxonomy).

Thank you again for your time and effort, and for helping us improve the manuscript.