COMPARING QUALITATIVE ANALYSIS TECHNIQUES FOR CONSTRUCTION ENGINEERING AND MANAGEMENT RESEARCH: THE CASE OF ARCTIC WATER INFRASTRUCTURE

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ABSTRACT

Construction is a dynamic sociotechnical process, consisting of ongoing interdependencies between people and the built environment. Accordingly, finding solutions to construction challenges when they arise requires understanding the interactions between social and technical factors. Over the past three decades, qualitative methods have been increasingly applied in construction engineering and management (CEM) research to understand challenges within this industry. However, there remains a lack of resources in the CEM literature on qualitative method selection and implementation specifically applicable to this domain. Without such guidance, it can be challenging to choose the most appropriate research methods, which can limit theoretical and practical contributions. To begin to address this gap, this paper offers an overview and comparison of three qualitative data analysis techniques—ranging in their use of induction, prevalence in CEM research, and ability to answer different types of research questions. These analysis techniques are applied to the same semi-structured interview data drawn from a case study on rural Alaskan water infrastructure. Insights gained from each method are compared to illustrate the utility of each technique. To the authors' knowledge, this study is the first qualitative method-comparison paper published for a CEM audience. Based on the comparison findings, choosing a deductive content analysis can allow for full characterization and quantification of a data set and discussion of results in relation to a predefined framework, such as a framework based on design and construction standards. A hybrid content analysis can expose new, detailed insights for an existing framework by allowing emergent themes to arise and be quantified. Conversely, a constant comparative analysis can reveal emergent trends and uncover the reasons why these trends occur based on connections between prominent themes, which can help CEM researchers develop new theories. Overall, this study helps advance the sociotechnical side of CEM research by enabling the discipline to better address the industry's complex challenges.

KEYWORDS: qualitative methods; constant comparative analysis; content analysis; method comparison; water infrastructure; operations and maintenance

INTRODUCTION

Increasingly over the past three decades, qualitative methods have been applied in construction engineering and management (CEM) research (Agyekum-Mensah et al. 2020). There has been a growing appreciation that construction is a social process, involving people and social elements at all stages—from the design and building of infrastructure to its management, operation, and use (Abowitz and Toole 2010). Consequently, finding solutions to construction challenges requires understanding the interactions between these social and technical factors (Phelps and Horman 2010). Qualitative methods have been used to explore a variety of sociotechnical challenges across a range of diverse CEM topics, such as workplace dynamics (Brockman 2014), project delivery during emergency response (Kosonen and Kim 2018), and megaconstruction projects (Erol et al. 2020).

Despite the increasing application of qualitative methods in CEM research, there are opportunities to further bridge the gap between the social science and CEM domains (Bresnen et al. 2005; Dainty 2008; Kelly and Bowe 2011; Koch et al. 2019; Sherratt and Leicht 2020). This is an ongoing challenge for CEM researchers, who often have highly quantitative, disciplinary-specific training, to learn and implement social science techniques—what Koch et al. (2019, p.314) refer to as "danc[ing] across disciplinary boundaries." The challenge of applying qualitative methods to CEM research likely persists due to the dearth of resources instructing CEM researchers on why and how to perform such analyses. Although social science researchers have published extensively on qualitative methods, there is a systemic difference in the underlying logic of inquiry and research between CEM and many social science disciplines (Szajnfarber and Gralla 2017), which can make cross-discipline communication and learning difficult. For example, construction management as an academic field is more problem-driven than a paradigm-driven field such as organizational ecology (Bresnen 2017; Schweber 2016), meaning the scope and aims of CEM research often have a normative orientation and strong connection to practice (Koch et al. 2019). Consequently, without CEM-specific resources, CEM researchers who are new to qualitative research, but who have valuable, context-specific expertise, may not be able to differentiate between different types of qualitative methods and know when and how to implement each of these techniques in their research. Moreover, they may be unaware of or feel ill-equipped to apply less familiar methods to the CEM literature, which may stymie the development of a more mature CEM research discipline (Sherratt and Leicht 2020). This paper offers CEM-specific guidance for choosing and implementing qualitative analysis techniques by describing, applying, and comparing the findings generated by three different analysis methods. These qualitative methods vary in three ways: 1) popularity within CEM research, 2) use of induction, and 3) ability to address different research questions, and the comparison occurs using the same semi-structured interview data from a CEM research study. To the authors' knowledge, this paper is the first qualitative method-comparison paper published for a CEM audience, helping to bridge the gap between social science and construction disciplines.

POINTS OF DEPARTURE

The value of qualitative research in CEM

Qualitative research is a pluralistic term, describing many research methodologies (theories of how inquiry should proceed) and methods (procedures to generate and analyze data) often used to explore and build hypotheses around holistic pictures of social or human problems (Corbin and Strauss 2008; Creswell 1998). For this reason, qualitative inquiry is valuable to CEM research. Construction is a dynamic sociotechnical process, consisting of ongoing interdependencies between people and the built environment at the design, construction, operation, and management stages (Davis et al. 2014; Pirzadeh et al. 2021). These processes are complex, not only because of their many moving parts, but also because of their human and social elements. To illustrate this point using a contemporary example, the authors consider the operation and management of water utilities in the United States that were influenced by COVID-19 social distancing policies. When enforced, these policies altered human behaviors such that there were spatial and temporal shifts in drinking water demands (Bakchan et al. 2022; Spearing et al. 2021; Zechman Berglund et al. 2021). Utilities' responses to these changes included modified workforce management, delayed capital projects, and adjusted maintenance protocols (Spearing et al. 2020). Furthermore, many local governments implemented regulations ensuring access to services regardless of users' abilities to pay for water, which resulted in decreased revenue for many utilities. Rather than use quantitative methods to describe the demand shifts and revenue losses in numerical indices that model *what* happened statistically, the researchers exploring these unprecedented situations used qualitative methods to understand *how* and *why* changes impacted utilities. In these ways, this work demonstrated the strength of qualitative research by generating practical planning recommendations to utilities with an understanding of the implications of each, having investigated the nature—rather than mere existence—of the utilities' challenges (Spearing et al. 2020). In addition, qualitative inquiry is useful for identifying and developing theories around new phenomena (Glaser and Strauss 1967; Phelps and Horman 2010), which is important given the relative nascency of the CEM research discipline (Fellows and Liu 2015).

Opportunities for expanding qualitative research in CEM

Integrating social science methods in CEM research can be challenging (Koch et al. 2019). Typically, CEM researchers are not formally trained as social scientists and have limited, if any, training in qualitative research (Kelly and Bowe 2011; Toole 2007). It requires skill and experience to apply social scientific thinking in CEM research contexts. While CEM scholars new to qualitative research can learn from an ever-growing body of CEM literature applying qualitative methods (e.g., Cruz Rios et al. 2021; Pirzadeh et al. 2021; Pons et al. 2021) and describing qualitative approaches (papers such as Abowitz and Toole 2010; Gibson and Whittington 2010; Phelps and Horman 2010; textbooks such as Fellows and Liu 2015), they may still have difficulty selecting an appropriate analysis technique to answer the research question at hand. To the authors' knowledge, there has yet to be a comparison of the utility of different qualitative analysis methods within the same CEM-relevant study context. This type of comparison would provide CEM researchers with an understanding of the strengths and weaknesses of different methods, including their varying abilities to address different types of research questions—knowledge that would strengthen their ability to choose an analysis technique based on its utility rather than popularity within the CEM research community. To use a common analogy, one of the best ways to know that a hammer is superior to a screwdriver for driving a nail into a wall is if both are tried and the results are compared. While any qualitative analysis technique may arguably provide some understanding of the social phenomenon of interest, the method chosen may not be optimal in its ability to contribute to theory and/or practice.

Purpose

The objective of this paper is to apply three different analysis techniques to the same qualitative data to compare the strengths and limitations of each method. By doing so, this paper provides guidance to CEM researchers as they choose and conduct qualitative analysis by illustrating what unique insights each method can offer CEM researchers. While the authors use semi-structured interview data, which is common in CEM literature (Dainty 2008), the analysis techniques could be readily used with textual data collected through other means (e.g., focus groups (Liang et al. 2018), documents (Palagi and Javernick-Will 2020)). The authors draw the data from a case study on water infrastructure operations, management, and maintenance (OMM) challenges in rural Alaska. The three techniques include a deductive qualitative content analysis, a hybrid qualitative content analysis with additional inductive coding, and a constant comparative analysis through grounded theory. These methods represent a range of techniques with differing levels of deduction/induction, prevalence within the CEM literature, and relevance to answering different types of research questions. Such variety helps both build on existing trends and encourage methodological expansion of the field, in accordance with calls for more diverse research paradigms (i.e., frameworks) in CEM research (Bresnen et al. 2005; Pink et al. 2010; Sherratt and Leicht 2020).

BACKGROUND

In this section the authors define the three analysis techniques and provide examples of their use in the CEM research. Two approaches are categorized as content analysis, which is a family of approaches for analyzing text (Hsieh and Shannon 2005; Rosengren 1981). There is no one way to define content analysis, and different fields use various nomenclature to describe this method. The major differences in the process of performing the varying approaches are in the coding schemes, origins of codes, and techniques addressing trustworthiness (Hsieh and Shannon 2005). These methods can be used to answer different types of research questions, while bearing in mind that these different types should be broad, open-ended, and asking "how," "what", or "why" questions. The method chosen should align with the researcher's purposes to ensure the study is logical and coherent (Koch et al. 2014).

Deductive content analysis

To begin, the authors focus on a deductive approach to content analysis that emphasizes the quantification of what the data communicate (Krippendorff 1989; Lasswell et al. 1952), in addition to the who, why, how, and consequences (Holsti 1969; Krippendorff 1989). These approaches may be considered positivist in nature, though given that the data "do not have a single meaning waiting to be unwrapped," as Krippendorff (1980 p. 22) claims, interpretation of the text is still necessary (see also Fellows and Liu 2015). With this deductive approach, researchers use a pre-defined coding scheme based on existing theory or research to assign pre-segmented interview data, or units of analysis (Krippendorff 1989), to codes and present the frequencies of these codes in tables, interpreting them as indicators of relative importance. It is important to note, however, that when using interview data, the frequency can also reflect greater willingness or ability for participants to talk at length about a topic (Joffe and Yardley 2004). Deductive content analysis may be particularly useful for answering focused research questions along the lines of, "How is this phenomenon, as described in the chosen theoretical framework, identified in the narratives of the participants (Boman et al. 2015)?" CEM researchers have used this approach to analyze various types of data, including survey, semi-structured interview, and contract data (e.g., Fuller et al. 2018; Jayasinghe and Ramachandra 2016; Ragab and Marzouk 2021).

In terms of rigor, researchers employing deductive content analysis are often concerned with intercoder reliability (Burla et al. 2008), which relates to the stability of the findings (Altheide and Johnson 1994; Whittemore et al. 2001). More precisely, intercoder reliability is a measure of agreement among multiple researchers for how they assign codes to units of analysis. Intercoder reliability is useful for reducing bias and identifying weaknesses such as imprecise code definitions (Burla et al. 2008; MacPhail et al. 2016). There are several related statistics that are often calculated to assess the quality of coding (Burla et al. 2008), including Cohen's kappa (Cohen 1960), Krippendorff's alpha (Krippendorff 1970), and Mezzich's kappa (Mezzich et al. 1981). While Cohen's kappa is popular, it is limited in its ability to correct for chance agreement between coders and in its requirement that each unit of analysis must only be assigned one code (Krippendorff 2004). Though Krippendorff's alpha, which measures observed and expected disagreement rather than agreement (Artstein and Poesio 2008; MacPhail et al. 2016), is not limited in these ways, it is computationally intensive. A lesser-known option is Mezzich's kappa, which is a modification of Cohen's kappa in that it relaxes the assumption of mutual exclusivity (Eccleston et al. 2001; MacPhail et al. 2016; Mezzich et al. 1981). Rather than use these types of statistics, some researchers may prefer to calculate percentage agreement, as it is simpler; however, this is not recommended, as it consistently overestimates agreement by not accounting for chance agreement between coders (Hruschka et al. 2004; MacPhail et al. 2016).

Regardless of the statistic chosen, the intercoder reliability process is often iterative and time-intensive and may occur more than once during the coding process. The process often begins with researchers establishing the coding rules (e.g., Can multiple codes be applied to the same text segment?) and units of analysis (e.g., Will the text be segmented into paragraphs, responses to questions, sentences? (Milne and Adler 1999; Roller and Lavrakas 2015)). In deductive content analysis, the researchers analyze text using codes that are deductive, originating from an existing framework (Elo and Kyngäs 2008). After the main coder completes a portion of the coding, other researchers may independently code predetermined portions of the total transcripts (Campbell et al. 2013; Lacy and Riffe 1996; MacPhail et al. 2016). If there is large disagreement between the researchers, the codebook is be refined and the process repeated with additional transcripts (MacPhail et al. 2016). The iterations may continue until a satisfactory level of intercoder reliability is achieved (i.e., when a sufficiently high statistic is attained). Once the primary coder recodes all of the transcripts with the refined codebook, a final intercoder reliability check may be completed. The reader is encouraged to explore the referenced articles to further understand the value and steps involved in assessing intercoder reliability.

Hybrid content analysis: deductive content analysis with additional inductive coding

Another approach to content analysis is a mixed deductive and inductive design. Researchers using this approach not only code deductively using a conceptual framework, theory, or research goals (Saldaña 2013), but also generate new or emergent themes (Burla et al. 2008). This approach may be useful for answering research questions along the lines of, "How well does this existing framework describe the experiences of the participants (Hsieh and Shannon 2005)?" While hybrid deductive-inductive designs are common among some CEM researchers (e.g., Palagi and Javernick-Will 2019, 2020; Spearing and Faust 2020), they are not often paired with content analysis specifically, suggesting this combined approach has the potential to contribute new perspectives to the field. In terms of establishing validity, the method is flexible and varies by field. For example, some CEM researchers using mixed deductive and inductive techniques (not necessarily for a content analysis) report intercoder reliability statistics calculated with all of the deductively and inductively derived codes (e.g., Davis et al. 2019; Spearing et al. 2021; Spearing and Faust 2020); however, it is difficult to obtain high intercoder reliability with codes generated inductively (Bengtsson 2016; Catanzaro 1988). Other social science fields such as communication studies may suggest calculating intercoder reliability for deductive codes and then examining coding consistency across multiple researchers to assess the emergent themes (Potter and Levine-Donnerstein 1999; Stephens 2017). Important to note, while both intercoder reliability and coding consistency aim to improve the quality of coding and reduce subjective bias, they differ in their assessment process. Intercoder reliability is the calculation of a reliability statistic generated when another researcher independently double codes a predetermined portion of the data (often randomly selected). Coding consistency and validation processes use a second researcher to conduct an in-depth review of the initial coding performed by the first researcher; the coders agree on any revisions, and they verify that the same core categories emerged.

Grounded theory through constant comparative analysis

Grounded theory provides a systematic inductive qualitative approach to data collection, coding, and analysis that can derive core conceptual categories and explore interactions between these categories, ultimately aiming for theory development (Charmaz 2006; Corbin and Strauss 1990). Strauss (1998) recommends asking research questions along the lines of, "What is happening here?" Similarly, Glaser (1998) suggests, "What is the main concern and how is that concern continually resolved or managed (McCallin 2003)?" Charmaz (2006) recommends allowing research questions to change during the process of research to reflect an increasing understanding of the problem being researched (Agee 2009). Guided by the research questions or objectives, the derivation of core categories is performed through constant comparative analysis using two coding procedures: open coding and focused coding (Glaser 1965). Open coding involves reading the transcripts and attaching data segments, referred to as excerpts, to conceptual components that summarize their contexts, referred to as open codes. Following this process, researchers apply focused coding by constantly comparing the generated open codes with each other; by considering corresponding excerpts, researchers can identify common properties that can be used to group them within individual categories (Glaser 1965; Glaser and Strauss 1967). Categories generated at the highest aggregation level are referred to as core categories. Following the application of focused coding, axial coding is applied to explore the relationships between the emergent core categories, by iteratively revising the generated excerpts until they hold true for all coded interviews (Charmaz 2006; Corbin and Strauss 1990). Once theoretical saturation is reached (i.e., no new core categories and relationships among them emerge (Charmaz 2006)), the analysis can be used to extend or develop theory. Constant comparative analysis and grounded theory have been used widely in CEM research, spanning topics such as the safety and health of construction workers (Chan et al. 2016), engineer-procure-construct projects (AlMaian et al. 2016), megaconstruction projects (Erol et al. 2020), critical thinking in engineering practice (Osman et al. 2020), and utility operation in humanitarian contexts (Bakchan et al. 2021).

Rather than using intercoder reliability statistics, validity in constant comparative analysis and grounded theory is driven by establishing trustworthiness through criteria such as coding consistency across multiple researchers that could help reduce subjective bias (Bernard 2017). This approach to coding consistency and validation involves joint coding with multiple investigators (Glaser, 1965) to produce more systematic theory development.

METHODS

The following methods section describes the application of the three qualitative approaches to the same semi-structured interview dataset. The research objective is to apply and compare the different methods; in pursuit of this, the authors specify a sub-research objective that is addressed by each of the three methods. By holding the research objective and data constant, this paper is able to illustrate what the different methods can offer. While this approach is appropriate for a method-comparison paper, for typical qualitative research the authors recommend that methods be selected based on the research questions (Agee 2009). It is important to note that the methods focus of the paper also means that in the discussion section the authors concentrate on describing what each approach can offer CEM researchers doing qualitative work rather than describing the implications of the findings for the water sector. To provide additional assistance to CEM researchers new to qualitative research, the authors provide a list in the Supplemental Information (SI) outlining best practices and guidelines for project design, interview data collection, and data analysis phases.

Project Design and Data Collection

To demonstrate each qualitative approach, the authors used eight semi-structured interviews collected as part of a larger project focused on identifying factors influencing water infrastructure challenges in rural Alaska. The authors compared the insights gained from each approach when addressing the following research objective: To characterize the nature of operations, management, and maintenance (OMM) challenges in rural Alaskan water systems. The interview data is inclusive of both piped and decentralized water systems.

OMM challenges in Alaska are sociotechnical in nature and therefore well-suited for qualitative research methods. In rural Alaska, maintaining water systems can be challenging

(Richardson 2013) due to factors such as workforce limitations, supply chain constraints, and financial limitations (Sohns et al. 2021). For example, revenue from end-users typically sustains the OMM of a piped water system, which may be difficult to obtain in communities that are not primarily cash-based or operate with a subsistence economy. In addition, water system OMM requires technical expertise and training that is often limited in rural settings (Hickel et al. 2018).

Prior to data collection, the authors received institutional review board (IRB) approval from The University of Texas at Austin, The University of Washington, and the Alaska Area IRB. The semi-structured interviews were conducted with state and local regulators, as well as other subject-matter-experts (e.g., employees of nonprofits operating in this space). Interviewees were selected using convenience and snowball sampling until theoretical saturation was reached (Corbin and Strauss 2008). For the current analysis, eight interviews from the full dataset were selected based on the interviewee's expertise in OMM. Table 1 in the SI presents information about the interviewees.

Interviews were conducted from January 27, 2021, to June 2, 2021, through virtual conferencing. On average, interviews lasted 58 minutes. The interviews were recorded, transcribed, and reviewed for quality (i.e., checked that the transcript matched the audio). The interview protocol focused on water infrastructure challenges and consisted of questions such as: What water infrastructure challenges are you aware of in regard to access or levels of service in rural Alaska? Can you describe service disruptions or failures that commonly occur? What workforce challenges do you face with your water infrastructure systems operations and maintenance in rural Alaska?

Four researchers were involved in analyzing the data used for the method comparison. Two researchers focused on the content analysis, and two separate researchers, not involved in the data collection, focused on the constant comparison analysis. By segregating the analyses, and not discussing the findings until the analyses were complete, the findings reflect real-world approaches where typically only one of these analysis approaches is chosen.

Deductive Content Analysis

The first analysis approach was deductive content analysis. For this method, the authors used a coding framework/dictionary based on the US Environmental Protection Agency's (US EPA's) Capacity for Drinking Water Systems nomenclature (US EPA 1998). The US EPA states that technical, managerial, and financial capacity are needed to maintain long-term sustainability and compliance of water systems. It decomposes each of these three dimensions into several descriptive sub-categories. For example, the financial category consists of credit worthiness; the managerial category consists of effective external linkages; and the technical category consists of infrastructure adequacy. Consequently, the authors coded OMM challenges to these sub-categories under technical, managerial, and/or financial (see Table 2 in the SI for category definitions). The unit of analysis is the complete response to the interviewer's question at hand. Each unit of analysis could be assigned one or more codes (i.e., simultaneous coding; Saldaña 2013). NVivo software was used to structure and organize the qualitative coding (*NVivo* 2020).

The full content analysis was performed by one researcher. When the researcher finished coding half of the interviews, a second researcher independently coded two interviews using the coding dictionary. The two researchers then resolved discrepancies between coding and updated the coding dictionary, refining the emergent code definitions under the EPA-based deductive codes. After the primary researcher (re)coded all eight transcripts based on the new dictionary, a second intercoder reliability check was completed using two interviews. This check was iterative and when the researchers agreed on a final codebook, the coding was updated for all interviews.

Given that multiple codes were able to be assigned to each unit of analysis, the authors calculated Mezzich's kappa and obtained a statistic of 0.68, which is considered suitable for exploratory qualitative research (Burla et al. 2008; Everitt 1996).

Hybrid Content Analysis: Deductive with Additional Inductive Coding

Using the deductive content analysis as a starting point, the authors inductively coded emergent challenges (Table 1), taking a data-driven approach (Saldaña 2013). This method is a mixed deductive and inductive approach, employing the EPA guidance (US EPA 1998) as the framework to classify the data into codes and then allowing for themes to emerge within each deductive code. Simultaneous coding was used to characterize the data, allowing an excerpt to be coded to multiple categories (Saldaña 2013). Coding was again done in NVivo software (*NVivo* 2020).

To validate this analysis, the researchers paired the Mezzich's kappa test previously calculated for the content analysis with an in-depth review of lower-level codes. Two researchers coded two interviews independently and compared the emergent codes for consistency (Bernard 2017). This process consisted of multiple meetings and over four hours of discussion, with the dictionary being updated after each meeting.

Constant Comparative Analysis

Through constant comparative analysis, the authors derived core categories that corresponded to major OMM challenges. Given the methodological scope of the paper, the authors did not present a developed theory from the constant comparative analysis. The authors began by having one researcher open code the eight interviews, attaching excerpts to phrases that summarized their contexts (Glaser 1965). A second researcher then examined these open codes and added more codes to this raw data set. The two researchers aggregated the open codes into higher-level categories through multiple rounds of focused coding following a systematic process (Glaser 1965; Glaser and Strauss 1967). As part of the process, each focused code was compared against one another and aggregated into core categories. Following this, the researchers applied axial coding to identify the interactions between the emerged core categories (Charmaz 2006; Corbin and Strauss 1990); refer to the Analysis Techniques section for further details about the various coding procedures. Important to note, validity was achieved by having the second researcher revise the initial coding performed by the first researcher to ensure that consistent core categories were derived.

ANALYSIS RESULTS

The following sections present the results of each analysis technique, including the figures, tables, and brief examples of how the results may be interpreted.

Deductive Content Analysis

Table 1 shows the frequency table of OMM challenges present in each code based on the US EPA's Capacity Nomenclature (US EPA 1998); see the SI for definitions and examples of each code. It is important to note that the frequencies may not indicate that certain challenges are more important or prevalent, rather that they were discussed more by interviewees (Joffe and Yardley 2004). Overall, it was found that financial, managerial, and technical OMM challenges were mentioned frequently by respondents, with most excerpts being coded to technical adequacy (41%). This finding is not surprising given the technical difficulties associated with the Arctic climate and the issues with technical knowledge in the workforce (Hickel et al. 2018; Sohns et al. 2021). Challenges with managerial adequacy were mentioned by all interviewees, with staffing and organization being the most discussed (32% of excerpts coded to the managerial code). Within the financial category, many respondents spoke of the lack of access to capital (i.e., credit worthiness) and challenges with revenue sufficiency (i.e., how much their revenue covers costs). These major trends display overall challenges to financially support water systems that are costly to operate and maintain.

[Insert Table 1]

Hybrid Content Analysis: Deductive with Additional Inductive Coding

Tables 2 and 3 show the expanded frequency tables of codes that emerged under the revenue sufficiency and staffing and organization codes. These codes were selected due to their similarity with those that emerged from the constant comparative analysis, allowing for comparison between methods. Similar to the deductive content analysis, high frequencies do not mean that challenges are more important, but that they appeared more often in the data.

The high cost to maintain systems was discussed by all interviewees and comprised the majority of the excerpts coded to revenue sufficiency (68%). Table 2 shows that high operating cost was related to multiple factors such as heating costs, operator errors, and supply chain. For instance, one interviewee described that piped systems require "heating the water, circulating water, pumping water and wastewater" which is "very expensive in communities where the primary source of power are diesel powered generators." Interestingly, some interviewees (25%) mentioned that operator errors led to increased operating expenses, such as the use of extra heat after a freeze-up rather than repairing the infrastructure.

In addition to revenue sufficiency challenges, all respondents discussed challenges with staffing and organization (Table 3), including challenges to hire and retain operators and workforce mobility issues (e.g., remote nature of communities makes access difficult for maintenance workers). Half of the respondents mentioned that the inability to have a backup operator was a challenge. For example, one interviewee remarked, "What if [the operator] wants to take a vacation, but there's only enough money for one person to go out of the village to get the training and be certified? If they want to go take a vacation, there's nobody else trained and certified to be the operator."

[Insert Tables 2 and 3]

Constant Comparative Analysis

Open coding resulted in 480 open codes. Using focused coding, open codes were condensed into five core categories, corresponding to major OMM challenges that emerged from the data (Table 4).

[Insert Table 4]

Table 5 displays the major sub-categories that emerged within *Core Category 3:* Difficult to operate and repair water infrastructure. For instance, many interviewees mentioned that limited OMM skills and expertise within their communities due to inadequate training hinders operators' ability to respond to complex technical constraints (e.g., technical issues in treatment plants). Additionally, due to the extreme environmental conditions in Alaska, supplies required for operations and maintenance are often delayed, thereby impeding timely repairs to technical issues. For example, an interviewee stated, "Delays are a fact of life in rural Alaska, sometimes there's one little piece you need, and you're three weeks out. Some of the pumps you buy can be six weeks out easily. You know, getting materials to the village is always a challenge."

[Insert Table 5]

Figure 1 illustrates the direct relationships across the emerged core categories identified using axial coding. For example, all of the interviewees mentioned that agencies do not fund OMM projects and sometimes implement projects that do not actually consider the climate constraints in the Arctic (e.g., funding projects to be built on flood plains). The limited OMM funds (or lack thereof), in turn, hinders the implementation of much-needed operation and maintenance activities within the Alaskan communities, creating a misalignment between funders' priorities and the actual needs of these communities. Such constraints surrounding OMM funding, as well as the year-round extreme climate, exert a large burden on Alaskan communities to perform normal operations and maintenance activities. These observations can be interpreted as follows (Figure 1): a relationship directed from "disconnection between funding agencies and communities' needs" to "difficult to operate and repair water infrastructure," and another relationship directed from "extreme and changing climate" to "difficult to operate and repair water infrastructure."

[Insert Figure 1]

DISCUSSION

In this section, the strengths and weaknesses of each approach are considered by comparing between results. Opportunities for strengthening qualitative CEM research are also discussed.

Strengths and Limitations of Analysis Techniques

Deductive content analysis

A primary strength of the deductive content analysis is its ability to understand the research question/objective through an existing theoretical or practical framework (Elo and Kyngäs 2008; Krippendorff 1989). Here, the authors used nomenclature from the EPA's Capacity Development Program to generate the coding dictionary. This nomenclature (technical, managerial, and financial) is used to (1) regulate new systems, (2) inform capacity development strategies, and (3) assess the capacity of systems to inform funding decisions (US EPA 1998). By using this framework, the authors were able to view challenges through the same lens that policy and funding decisions are made. Illustratively, the analysis demonstrated that fiscal management and controls and ownership accountability were not frequently mentioned in the interviews (5 and 7 responses spanning 8 interviews, respectively). Both of these aspects pertain to how the utility is managed administratively. For example, the fiscal management and controls category is largely concerned with budgeting, which may not be an important part of capacity development if the community is largely a subsistence economy, a common occurrence in Alaska. The results indicated that this EPA-driven framework may need to be adapted when used in the Alaskan context, especially when relied on to determine which utilities receive loans, as this may penalize systems that are unable to comply with certain capacity requirements (e.g., maintaining financial records). In these ways, the deductive content analysis allowed us to create actionable policy recommendations.

Yet, a deductive content analysis may be limited in its discovery of emergent ideas and in its ability to help researchers understand reasons and relationships. For example, the authors were unable to uncover why utilities struggled with revenue sufficiency, or how technical, managerial, and financial capacity link together. Furthermore, when using a deductive content analysis, the interview data may not fit clearly into the framework used, which may introduce bias as the researcher tries to force the data to fit.

Hybrid content analysis: Deductive with additional inductive coding

Similar to the deductive content analysis, the hybrid content analysis allowed the researcher to make connections to the pre-defined EPA-driven framework. However, unlike the purely deductive approach, the hybrid approach characterized each piece of text based on emergent themes, allowing new information to arise beyond the scope of the pre-defined categories. For example, the analysis demonstrated that not only were there issues with revenue sufficiency, but also that these issues were caused by the high cost to operate systems and the inability of communities to financially support the systems. Furthermore, the authors were able to identify why operation costs were high, due to reasons such as operator errors, Arctic conditions, or the remote locations (Table 2). The hybrid approach also enabled quantification of the data displayed as frequency tables. For instance, when describing staffing and organization challenges, the researcher was better able to convey how often codes were mentioned: 88% of interviewees mentioned it was hard to hire and retain operators due to their inability to pay them a fair wage, 50% spoke of the small job pool in rural areas, and 38% raised the fact that many operators practiced subsistence farming.

The hybrid approach's weaknesses are similar to those of the deductive approach. First, there is still a researcher-imposed framework that could introduce bias. Second, the hybrid approach does not uncover relationships between codes, and instead captures the aggregate details of the data set. For example, the analysis revealed that the high OMM costs for water systems were associated with climate change, the Arctic climate, and operator errors, among other reasons (Table 2), but did not reveal connections between these ideas. For instance, the authors were unable to understand what contributes to these operator errors—was it a lack of training or the limited labor pool? Although the authors could reference findings in other sections such as the hiring and retaining operators category (Table 3) to make connections, the analysis could not reveal these by design. Third, compared to the deductive content analysis, the hybrid approach is more time-intensive.

Constant comparative analysis

The constant comparative analysis' robust bottom-up abstraction procedure—starting inductively from open codes and continuing towards higher-level categories—allows scholars to understand the *why* behind the issues of concern. Here, the authors identified major challenges to water infrastructure in rural Alaska, as well as understood why these challenges occurred. For instance, a communities' ability to repair operational issues in a timely manner is often hindered by supply chain constraints in the extreme environment and limited local OMM skills and expertise. In addition, this approach can help researchers identify relationships between core categories, allowing for a large-scale, comprehensive analysis. Although both the hybrid content analysis and the constant comparative analysis reveal that the extreme and changing climate is a challenge (e.g., high cost to operate, maintain or replace systems due to Arctic conditions and climate change in the content analysis; *Core Category 5* in the constant comparative analysis), the relationships between this challenge and other challenges were not discovered through the hybrid content analysis. The constant comparative analysis, however, showed that the physical infrastructure is adversely impacted by the extreme and changing environment (e.g., foundations and structures are becoming unstable due to melting permafrost; see Figure 1, direct relationship from *Core Category 5* to *Core Category 4*). The fact that the physical infrastructure is not adapting to the extreme and changing environment, in turn, has increased the need for more effective operation and maintenance activities, which Alaskan communities are already struggling to achieve (see Figure 1, direct relationship from *Core Category 4* to *Core Category 3*). The ability to derive such connections between core categories provides a better understanding of how the climate has influenced and exacerbated other major OMM challenges, a unique strength that is lost in the other qualitative approaches.

Despite the constant comparative analysis's comprehensiveness, details captured by the open codes were lost in the collapsing process done to create the core categories. As previously mentioned, over 480 open codes were generated—a number of codes that exceeds any other coding procedures shared here—but only five core categories were represented (Figure 1). However, it is important to note that these open codes and their corresponding excerpts remain available to the researchers to support the analysis as needed and to generate ideas for new analyses, too.

Another important point of comparison among the analytical approaches is the link to an existing theoretical framework. Constant comparative analysis is not driven by an existing framework, and the practical recommendations generated may differ from other analyses. The recommendations resulting from the constant comparative analysis primarily relate to the core categories that specifically address the *why* aspects identified through the detailed inductive analysis process. Finally, constant comparative analysis is not driven by quantification, nor does it generate frequency tables. This may be a limitation for studies interested in identifying how often themes are mentioned by interviewees, but that is something researchers could choose to count and include (e.g., Bakchan et al. 2021). Lastly, this inductive analysis approach is more time-intensive compared to the other approaches due to the multiple rounds of focused coding needed to condense and refine categories, as well as the rigorous coding consistency and validation process.

Opportunities and Recommendations for CEM Researchers

The following takeaways can help CEM researchers select the most appropriate data analysis technique. It is recommended that researchers intentionally choose their method based on their research question. The previous discussion of strengths and weaknesses can be used to guide researchers. Researchers should also consider the time and detail required of each approach. A summarized recommendation list of when to use each method is shown below.

- A deductive content analysis should be used if the goal is to quantify data and compare the results to an existing framework (e.g., EPA or LEED standards) or theory (e.g., ethical theories in construction engineering).
- A content analysis with additional inductive coding (hybrid approach) should be used to reveal new insights on a detailed scale, based on a research framework or theory. This

method is particularly useful if researchers want to quantify these emergent challenges. This hybrid approach could also be useful in mixed-methods studies which are becoming increasingly prevalent (Agyekum-Mensah et al. 2020) in the CEM literature (e.g., Odediran and Windapo 2017; Quelhas et al. 2019; Zhan and Pan 2020).

- A constant comparative analysis should be used for understanding large-scale emergent challenges and categories in a data set, as well as the relationships between them. The constant comparative analysis can be expanded using a full grounded theory analysis approach, which will enable CEM researchers to develop novel theories.

Limitations

As with any study, there are limitations to this research. First, the interview protocol was designed for a hybrid content analysis (deductive with additional inductive coding), yet three types of analysis were performed. Using the same data source may have caused some of the findings from the constant comparative analysis to be similar to the content analysis. Although this is a limitation, using the same interviews allowed for comparison between methods, providing valuable insights into the utility of each approach. Additionally, because only a subset of interviews was analyzed, theoretical saturation is not present in the data discussed in the results. However, the authors did not intend to contribute to the literature on water infrastructure in Alaska, and a paper on the full data set is forthcoming. Lastly, demographic data for each interviewee were not collected, limiting the understanding of biases in the data. The authors recommend that CEM researchers doing qualitative work with interviews collect demographic data when possible (Kaminsky 2021).

CONCLUSION

Although qualitative analyses of interview data are widely used in CEM research, there is a lack of guidance on the data analysis method selection and implementation processes. This paper addressed this need in CEM research by using three different qualitative analysis techniques—a deductive content analysis, a deductive content analysis with additional inductive coding (a hybrid approach), and a constant comparative analysis—and clearly explaining how these methods were applied. Using the same semi-structured interview data for all three methods, the authors compared the differences in insights gained from each approach to illustrate their utility (e.g., for answering different types of research questions), representing the first qualitative method comparison using empirical data on a topic relevant to CEM. This paper can serve as a resource for researchers to reference to better understand and choose an analysis technique. Overall, this study helps to advance qualitative CEM research, enabling the discipline to better address complex sociotechnical challenges.

DATA AVALIABILITY STATEMENT

All of the data used during the study are confidential in nature and may only be provided with restrictions (e.g., anonymized data). All codes are available from the corresponding author upon reasonable request.

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Table 1. Frequency table of OMM challenges in rural Alaska from deductive content analysis

Code	Number of Interviewees	Relative Frequency of Interviewees	Number of References	Relative Frequency of References
Total OMM Challenges	**8**	**100%**	**209**	**100%**
Financial	***8***	***100%***	***56***	***27%***
Credit Worthiness (or access to capital)	6	75%	15	27%
Fiscal Management and Controls	4	50%	5	9%
Revenue Sufficiency	8	100%	36	64%
Managerial	***8***	***100%***	***68***	***33%***
Effective External Linkages	6	75%	13	19%
Ownership Accountability	4	50%	7	10%
Planning	4	50%	10	15%
Staffing and Organization	8	100%	25	37%
Supply Chain	7	88%	13	19%
Technical	***8***	***100%***	***85***	***41%***
Infrastructure Adequacy	8	100%	57	67%
Technical Knowledge and Implementation	6	75%	18	21%
Water Source Adequacy	5	63%	10	12%

*The total of unique responses in each category will not be a sum of the columns because excerpts may have been coded to multiple categories.

** Relative frequencies are the percent of all excerpts coded to the broader code (e.g., Financial).

Table 2. Extended frequency table of emergent challenges with revenue sufficiency

Code	Number of Interviewees	Relative Frequency of Interviewees	Number of References	Relative Frequency of References
Revenue Sufficiency	***8***	***100%***	***37***	***64%***
High cost to operate, maintain, or replace systems	8	100%	25	68%
Due to Arctic conditions (e.g., heating costs, systems in permafrost)	*7*	*88%*	*12*	*48%*
Due to climate change	*4*	*50%*	*4*	*16%*
Due to operator errors	*2*	*25%*	*2*	*8%*
Due to remote location or supply chain challenges	*3*	*38%*	*5*	*20%*
Due to other reasons	*2*	*25%*	*2*	*8%*
Inability of communities to financially support the system (i.e., financially unhealthy)	6	75%	12	32%

*The total of unique responses in each category will not be a sum of the columns because excerpts may have been coded to multiple categories.
** Relative frequencies are the percent of all excerpts coded to the broader code (e.g., High cost to operate, maintain or replace systems).

Table 3. Extended frequency table of emergent challenges with staffing and organization

Code	Number of Interviewees	Relative Frequency of Interviewees	Number of References	Relative Frequency of References
Staffing and Organization	***8***	***100%***	***28***	***37%***
Getting and retaining operators	8	100%	19	68%
Due to financial capacity (e.g., low wages)	*7*	*88%*	*10*	*53%*
Due to small job pool (i.e., limited qualified and willing people)	*4*	*50%*	*6*	*32%*
Due to subsistence	*3*	*38%*	*3*	*16%*
Inability to have backup operators or multiple operators	4	50%	5	18%
Workforce mobility issues (e.g., remote workers)	3	38%	3	11%

*The total of unique responses in each category will not be a sum of the columns because excerpts may have been coded to multiple categories.
** Relative frequencies are the percent of all excerpts coded to the broader code (e.g., Getting and retaining operators).

Table 4. Coding definitions, including brief definitions of emergent core categories

#	Core Category	Definition of Core Category	Example Interview Excerpt (quotes indicate a word-for-word quote)
1	Disconnection between funding agencies and communities’ needs	Mechanisms for providing funds to water infrastructure (or lack thereof) and funding agencies’ areas of emphasis	*“There hasn't really been any funding from say, the federal government, who maybe funds the capital costs. They haven't been funding the operation and maintenance.”*
2	Lack of understanding of consequences of inadequate water access	Communities’ lack of understanding of consequences of inadequate access to water infrastructure, including poor water quality and health concerns	*“Generally, each community will have a primary [water] source and that's what you emphasize; you want to optimize on that primary source… We don't usually have a long history of water quality. For instance, if you're taking water from a creek or a stream, you wouldn't have much knowledge prior to your efforts to put a treatment facility that would produce safe water.”*
3	Difficult to operate and repair water infrastructure	Sociotechnical aspects that constrain the provision of water services and hinder adequate maintenance, including technical, social, financial, and institutional considerations	*“For a piped water and sewer system, you have to deal with [environmental constraints], and it requires heating the water, circulating water, pumping water… That is very expensive in communities where the primary source of power is diesel powered generators.”*
4	Physical infrastructure not adapting	Physical structure of water systems within areas and their conditions in response to extreme and changing environment	*If [permafrost] thawed, then you lose all of your support. So, you have problems with foundations, you have problems with pipes that are in the ground. That's going to be problematic if things continue to warm. It's going to be harder and harder to serve these areas that are already the most underserved.”*
5	Extreme and changing climate	Natural environment surrounding physical infrastructure and its status in response to climate change	*“Permafrost is always one of the biggest challenges when you're talking about environmental effects, and things [are] moving…. Like if you go to [that area], you're designing things that have to meet a delta T of negative 60 and plus 90”*

Table 5. Major sub-categories that emerge within *Core Category 3:* Difficult to operate and repair water infrastructure

Sub-category within *Core Category 3*	**Example Excerpt**
Supply chain issues	*"You essentially have to ship literally years' worth of chemicals and what you predict you're going to use for water usage, water production, etc. ... [For instance], if you're using alum, ferric chloride, HTH, or whatever, you've got to ship that stuff in one year at a time, ahead of time. So, it's not just about time; it's you order ahead, and most people want to be paid ahead."*
Transportation issues	*"Around 160 of these communities have no road access… So, they might get a barge in the summer, which is for the big stuff… If you want to ship HTH chlorine around, you can't put it on a passenger plane, you've got to essentially. So those kinds of chemical requirements, all you've got essentially put up nine months if you're down in [that area]."*
Lack of local OMM skills and expertise	*"Well, for operation and maintenance, … you're working in a small community with not a lot of individuals to draw from."*
Difficult to consolidate or share resources	*In [places outside Alaska], you call the technicians, and they can be there by truck and on that same day; but that's not true up here. It's a couple $1,000-trip if you want the controls man to come out and troubleshoot your system. So that kind of stuff always hampers … these folks.*
Expensive operation	*"Operating these systems is expensive and what ends up being sacrificed a lot is the salary for the operator."*

List of Figure Captions

Figure 1. Relationships across the emergent core categories