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INVESTIGATING HOW ENGINEERS AND DESIGNERS COMMUNICATE DESIGN RATIONALE

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ABSTRACT
Design rationale is the explicit documentation of the reasons behind decisions made in designing a product or system. Typically, design rationale is captured using a combination of written reports and oral presentations. Research shows that the structure and information used to communicate rationale significantly influence human behavior. To better understand the influence that communication of design rationale has on the design process, a detailed understanding of the information and techniques used to communicate design rationale needs to be studied. This research aims to identify how engineers and designers communicate this information in written form and the implications that their communication patterns have in engineering design. Eight hundred and forty-six pages of technical engineering design reports from 28 teams representing 116 individuals were analyzed using a mixed-methods approach and then compared across project types. The data were coded into categories using a schema we developed. The findings highlight the range of clarity that designers use in their rationales to support their design actions. Instead of clear, logical reasoning trends, designers often use techniques to fill gaps in design rationale through making assumptions, inserting oneself, or redirecting focus. The results suggest a need for improving design communication in engineering education and practice, perhaps through existing design reasoning frameworks or design rationale capturing tools. By capturing design rationale clearly between human designers, human-AI systems can leverage these findings to increase human confidence in and acceptance of a design agent's recommendations.

1. INTRODUCTION
Yarnoff et al. state, "A real design, as opposed to a fuzzy idea, is something you can articulate and explain to others [1]." A straightforward design rationale should back each design feature. Each rationale, in theory, should have evidence supporting it, usually in the form of design specifications determined via background research or interviews. Traditionally, the engineering design process cites clearly defining the problem, setting up design specifications, prototyping, and testing to determine whether each design specification was met [2,3]. Without explicit specification or design criteria, design decisions appear random and without a basis for each decision. Without this explicit design rationale, whether the decision was made logically or randomly is unclear.

Design rationale can reveal information about the design, the design process, individual designers, and the team. Engineering design is a disorderly process that is fundamentally argumentative in its reasoning, involving the negotiation of multiple preferences among a group of people [4,5]. Research suggests that the reasoning patterns designers use reveal the mental models held by those individual designers [6]. Mental models can change as new information is introduced [7], which means that design documentation provides a glimpse into the mental models held by a team. The designs created and processes performed are enacted by engineers and designers through their verbal or written language [8]. Research shows that designers need to shift effortlessly between abstraction and concretization when communicating design rationale. Depending on the project, an increase in domain expertise also needs to be conveyed [9,10]. Previous work in engineering design has found that information and tone used to support rationale affect human behavior [11–13].

To learn about the design rationale trends engineers use, the knowledge and methods of communicating rationale need to be investigated. Communicating design rationale in practice most often includes oral presentations and written documentation. Documentation and presentations are often met with less than excitement in the design process despite occupying a large portion of an engineer's time [14]. Mahan et al. found that engineers struggle to present ideas clearly, explain the purpose behind communication, or link sentences into logical paragraphs. Instead, lengthy and unorganized reports with hefty usage of jargon are commonplace [15]. Rarely will a single person oversee the entire design process; instead, engineers and designers need to work together and communicate with other members of a firm (e.g., technicians, sales, marketing). Without clear communication, a team that spent hours developing a new innovative product may never see the product advance to a later stage in the design process due to poor communication. A product can fail due to poor marketing and positioning. For example, the business side needs to understand how the proposed project brings value to the end-user. Often design communications are verbal in design practice; however, meaningful communication is written to state the meanings accurately and create a record for future reference [1].

This study aims to understand the communication methods used to explain the rationale behind a final design solution's features and functions. The central research question is:

> *How do engineers and designers communicate design reasoning in written documentation?*

A mixed-methods approach was used to analyze how design rationales are documented in final written design reports from three project-based courses. The coding process and sample codes are presented, showcasing the range of communication effectiveness and techniques used in documenting design rationale, and the implications behind these findings. Afterward, suggestions for improving design rationale communication in design practice and education are discussed, along with how these results can be applied within design support tools.

2. BACKGROUND

Communication is a central design activity [1]. Engineering design involves written, oral, interpersonal, numerical, and graphical communication [16]. Each aspect influences an engineer's ability to communicate how and why they performed design actions. Design documents tend to favor the technical aspects of the final solution without explaining the context of the process [17]. Design reports provide an opportunity to communicate design reasoning with a logical flow of the motivations and events that result in a final solution. Interpersonal conversations are often needed and helpful to uncover these aspects through questions and answers but are a more complex system of two or more people and their respective interpersonal skills. Documentation is indicative of a design team's ability to communicate. A firm usually sets the standard of the documentation. In engineering education, this is based on design practice but defined by the course instructors to meet the intended learning outcomes.

2.1 Studying Design Rationale

Studying design reasoning relies heavily on the data collection techniques used. For example, protocol analyses are commonly used in engineering design that asks participants to verbalize their thoughts while performing some task [18–20]. The verbalization of their thoughts and actions, in theory, represents the complexities of the cognitive process [21]. However, the limitation of protocol analyses, like other data collection forms, relies on a participant's communication ability. Considering humans can think much faster than they can verbalize those thoughts, the words spoken likely do not fully represent the complexity of the cognitive process [22]. Instead, the selected words correspond to the most salient thoughts to the designer in each moment.

This research leverages design documentation that designers have completed at their pace and should include enough content such that the document stands alone. Designers and engineers can revise as needed in written documentation before submitting, whereas informal conversations rely on quick thinking without time to practice. In engineering practice, design deliverables include presentations and final reports. Thus, within engineering education, course deliverables are modeled after industry practice and include multiple presentations and reports in addition to prototypes. The documented information is a selected curation of information that should be brief and to the point. These documents do not include the follow-ups or questions and answers that often-shed light on the nuances of decisions made. Sharing this information with new team members is often necessary. Depending on the industry or course, the written report may or may not need to be a standalone document.

2.2 Documenting Rationale for Design Support Tools

The design rationale engineers and designers use to communicate their design decisions holds promise in integrating human reasoning patterns into artificial intelligent (AI) applications. Current design support tools in development often mimic human design decisions but cannot clearly articulate the motivation or evidence supporting the designer's decisions, which the agent has learned and imitated [23–25]. By incorporating explanations based on human design rationale, a deeper understanding that combines what the agents are doing, design actions, and why the agents are doing so, design rationale, can help increase trust in AI systems within engineering design [26–28].

Devleena and Chaernova show that explainable rationale allows users to understand what the agent is suggesting and improves a designer's probability of using that suggestion, thus increasing task performance [13]. Research from Narayanan et al. explores what makes explanations from machine learning systems interpretable to humans to help increase trust and safety in these systems [12]. Furthermore, communication styles (assertive, commanding, informative) have significantly different outcomes in reported levels of trust [29]. Additionally, stereotypes and tones of the agent can also influence human-computer interactions [30,31]. Thus, multiple components of design reasoning presented and the form it is communicated have significant consequences on human behavior. In order to acquire the design rationale humans use, the rationales and modes of communicating rationale need to be studied.

3. MATERIALS AND METHODS

This mixed-methods study aims to understand how engineers communicate design reasoning in technical design reports. This section outlines the data collection process and the analyses used to code and visualize the data. Written technical reports from 28 design teams' containing three to five team members each are described. The data analyses used qualitative methods to identify emergent themes, while quantitative methods were used to visualize trends and relationships.

3.1 Data Collection

The dataset used for this study contained 846 pages of technical report documentation drawn from three project-based undergraduate and graduate engineering design courses at UC Berkeley. Fourteen undergraduate technical reports were gathered from two summer design courses, 2018 and 2019. Fourteen graduate technical reports were collected from a Fall 2020 semester-long course. The undergraduate students included a variety of disciplines (i.e., engineering and non-engineering) and mostly upper-level undergraduate students. Meanwhile, students were primarily mechanical engineering master's students in the graduate course, although a few undergraduates were in this course. Twenty-eight design teams comprising 116 students (Table 1) were taught about and engaged with the human-centered design process, including research, analyzing, ideating, building, and communicating stages.

TABLE 1: Breakdown of design team participants.

Year	No. of Teams	No. of Students	Demographic information
2018	6	28	Undergraduates
2019	8	33	Undergraduates
2020	14	55	Primarily graduate students
Total	28	116	

The instructors facilitated team formation in each class, resulting in design teams consisting of three to five students. Each design team could select their problem space and utilize any design methods and tools taught in the courses. The instructors and project mentors helped guide students throughout the design process. Each course had a series of learning modules and project deliverables. Project deliverables included but were not limited to design reviews, presentations, prototypes, and technical reports. The final write-up in each course had instructions to write up their problem space, the final prototype, and the design process the team underwent. The undergraduate course deliverable had an emphasis on the what and why behind design methods, while the graduate-level course included a comprehensive list of sections they could include in the report, although it was a guide and not a strict requirement.

For the undergraduate courses, due to a shorter course timeline, their reports were much shorter and less detailed (a total of 153 pages; approx. 10.9 pages/report) than those of the graduate course (a total of 693 pages; approx. 49.5 pages/report). The collection of these technical reports from three design courses serves as the primary data sources used in analyses. More specifically, increased attention was placed on reports sections that covered justifications behind design features, design specifications, and concept selection decisions. Colleagues from the research group who were instructors for the courses provided access to the reports after course completion. Students were not told who the researchers were. Identifiers for the technical reports were removed before downloading and analyzing the data. The institutional review board was notified and approved the data sources and methods.

3.2 Data Analysis

Document analysis is a qualitative research approach in which documents, in this case, technical design reports, were gathered and analyzed. The datasets were reviewed and coded by a single researcher with previous experience in engineering design research and design practice. More specifically, thematic analysis inspired by a grounded theory approach was used for coding the reports [22]. Figure 1 shows a high-level overview of the qualitative process used after collecting and importing datasets without any identifiers in MAXQDA, a software program for computer-assisted qualitative and mixed methods data, text, and multimedia analysis.

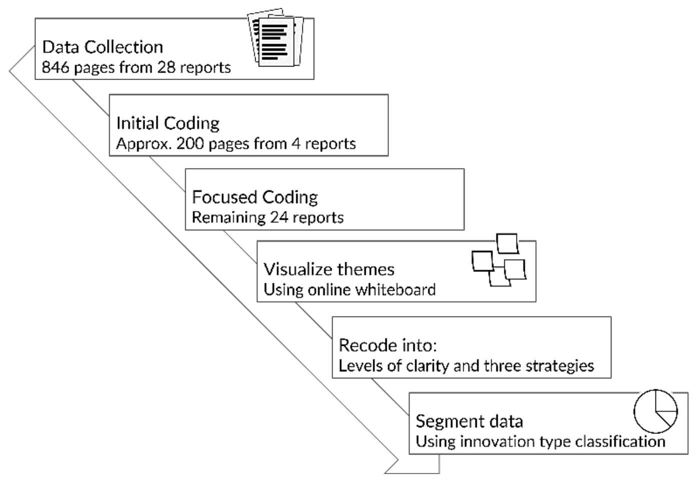

FIGURE 1: Overview of the research process. Note that the process is cyclic, and new codes, visualizations, and summaries of findings were created with each new data set.

The first step of initial coding was performed by closely moving through a portion of the data. For this stage, four reports from the graduate-level course (approximately 200 pages) were quickly coded regarding modes in which the design teams justified design decisions. By coding these reports, general focal points within each technical document were identified to contain relevant information to answer the intended research question of how engineers and designers communicate design rationale. Regions within the technical reports in which design rationale data was most concentrated occurred in design specifications, concept generation, selection stages, detailed descriptions of the prototype, and technical feasibility.

Observations were documented before beginning the focused coding portion on the remaining graduate-level documents, followed by the undergraduate design reports. Notes included information regarding the medium in which design rationale was communicated (i.e., text, images, tables) and persons or processes in which design rationale was generated. As focused coding was performed, two dominant relationships emerged as possibilities to situate the results and meanings. One approach was clarity in communicating design rationale, highlighting the medium and linguistic style used to communicate rationale. An alternative approach situates the themes as spatiotemporal benchmarks within the engineering design process where designers pinpoint rationale development via persons and methods within each design stage.

Code sets were created in this focused coding phase to group similar codes (i.e., created code group of missing information and associated codes like "missing links" and "overemphasizing language"). The resulting code sets include communicating clearly, missing information, inserting self, making assumptions, and redirecting focus. Afterward, a combination of concept charting and flowcharting was used to visualize the emergent themes using Mural, an online whiteboard platform. The visualizations related how clear and precise the communication of design rationale was and the techniques design teams used to describe and support their rationales.

Lastly, design team deliverables from the three courses were coded using the innovation type classification from Ceschin and Gaziulusoy [32], as noted in Table 2. A follow-up analysis was performed using the project classification to determine whether trends in design rationale communication could be attributed to project types, as Rao et al. used to understand design teams' justifications behind design method selection [33]. This follow-up analysis required each coded segment from the initial and focused coding stages to be accounted for within the emergent code sets.

TABLE 2: Innovation type and example projects [32].

Innovation Type	No.	Example project description
Product	13	A mask to help cyclists stay safe while cycling
Product-Service	7	An educational device and service that assists in remote learning
Spatio-Social	8	An intelligent seat reservation system that utilizes the existing indoor facilities to increase student experience
Socio-Technical System	0	—

4. RESULTS

This research aims to understand the patterns in communicating design rationale within final design reports. A qualitative approach was used to code and group emerging themes described as levels of clarity that detail the range of communication effectiveness in design rationale documentation. The results highlight coded examples of design rationale communicated clearly and design rationale with missing information. Lastly, three identified strategies that individuals appear to use in communicating design rationale are presented.

4.1 Clarity of design rationale varied across designers

A hierarchy in clarity of design rationale emerged from data analysis where segments coded as communicating clearly used more precise language than segments coded as missing information. Example codes and representative responses are shown in Table 3 and Table 4. Design rationale in this research and literature [1–3] is defined as explanations behind a design feature or function supported by evidence. The evidence source can vary (e.g., medical literature, user interviews, cultural norms). Table 3 shows the resulting code sets of interest and three example codes. The theme, communicating clearly, contained 109 codes in 22 of the 28 documents (79%), which means the remaining six documents are missing information when discussing rationale or not mentioning rationale altogether. The theme of missing information contained 115 codes from 27 documents (96%). There is a high frequency in which the design rationale is fragmented or missing across the majority of the reports.

TABLE 3: Resulting coding scheme based on 474 coded segments. In parentheses, the first number includes the codes' frequency, while the second number indicates the number of documents the code appears in of the 28 total technical reports.

Code set	Example codes
Communicating clearly (109; 22)	• communicating clearly • linking process • linking features with purpose
Missing information (115; 27)	• missing design requirements • missing source for specifications • lacking target group data
Making assumptions or generalizations (75; 25)	• sweeping statement • amplifying importance of problem • leaping rationale
Inserting personal experience or values (62; 24)	• inserting self as rationale • inserting personal values • creating their own criteria
Redirecting focus elsewhere (92; 24)	• pointing to table • listing specifications • alluding process

Communicating clearly: An example design rationale (shown as C1 in Table 4) was provided from a report in which the final product aims to assist wheelchair users while cooking. The coded segment states the product feature, the staging area, and mentions the design specification used to assess their design, which was to hold at least 20 lbs. of weight. Lastly, the design team directly links the evidence to support their decision, based on dish requirements commonly encountered by wheelchair users gathered through interviews and measurements they took with filling pots of water. These three elements (feature, specification, and evidence) were clearly laid out within the rationale, hence coded as communicating clearly—the highest level of clarity. The design team even includes the methods used to acquire the evidence. How this team communicates design rationale reveals that the team can communicate well and understand how different aspects of the design process intersect to inform their decisions.

Missing information: Rather than focus on how designers communicated well according to a traditional logical reasoning framework based on deductive reasoning, design rationale where parts or entire design rationale were missing are outlined in the following sections. The next tier of clarity highlights phrases where decision-makers link the motivation behind features and functions but do not connect the motivation to any evidence. This incomplete reasoning transfers the work to the report's reader to search the rest of the report for missing information. A report excerpt, M1 in Table 4, lists the product features and their requirements for the value for which the team designed. The evidence for these requirements is missing in the coded segment but can be found in earlier portions of the report that present the sources and mediums used to collect evidence and define the specifications.

The following examples show design rationales that appear cohesive but are missing parts of the design reasoning that would likely require follow-ups from their stakeholders. The entirely missing rationale only lists a design feature, for example, a project in which design teams created a garbage can that weighs food waste. A central feature is the ability to compute the weight of three separate compartments, which are customizable for whatever needs the user has. The waste reduction team provided detailed technical information to build the waste bin and emphasized the importance of the three compartments. However, no evidence in the remainder of the report suggested this was a need from users nor motivated by experts or literature.

Next, groups of design rationale emerged where only a portion of design rationale was missing, such as responses M2 and M3 from Table 4. In the first sentence, the design team concludes that users prefer their product more without providing evidence for that claim. No such behavioral data exists or interview quotes that lead the team to this conclusion. The existing solution was not documented in the report for this sanitizing product and was left for interpretation. Based on the context of the time and place of the class and users during COVID-19, the audience may infer the sanitizing solutions that the reader might have used early in the pandemic. The insights drawn by the reader are not guaranteed to be the same.

Moreover, another example from a separate design team alludes to processes or methods to explain their decision-making. The design team mentions using a Pugh Chart to select the top three ideas. In this case, the audience needs to refer to that chart in the report, despite no reference to a table, figure, or page number. The reader needs to skim the report to find the Pugh chart four pages down. Despite locating the weighted Pugh matrix, the motivation behind the criterion is not clear. The reader needs to reference the specifications defined earlier in the report. Upon reading that section, the reasons cited include the team feeling those specifications were most important.

At the surface, the varying levels of clarity showcase the spectrum of communication abilities. The coded rationales indicate an engineer's understanding of the process and purpose at a deeper level. When designers and engineers communicate well, they thoroughly understand what they did and why. Design teams with missing information in their rationale or entirely missing rationale point to poor communication abilities, a lack of understanding in their design processes and decisions, or both. They may simply not know why they modified the design or how their interviews influenced their change in direction. The varying levels of design rationale clarity indicate the degree of information designers assume their reader knows (i.e., team congruency or shared knowledge base). The levels of clarity highlight gaps in design communication that engineering education could address.

TABLE 4: Representative coded segments selected from within each code set used to present the findings of levels of clarity and three strategies used to communicate rationale.

Code set	Representative coded segment
Communicating clearly (C)	We determined that we need the staging area of the final product to hold at least 20 lbs. of weight, ideally with a 1.5 factor of safety or higher. This was determined based on the dish requirements commonly encountered by wheelchair users we interviewed, including pots filled with water. (C1)
Missing information (M)	Product feature. Partially opaque plastic maximizes diffusion of light, resulting in equal illumination. Requirement for security. Product means the cyclist is visible from 360˚, with no gaps in visibility. (M1)
	[Users] would prefer this product over their current sanitizing solution. (M2)
	Finally, we picked the top three ideas using a Pugh Chart as our final concept. (M3)
Making assumptions or generalizations (G)	Three metrics were not too overwhelming for the user to look at. (G1)
	The stylus is similar to a pencil that students would normally use at school. (G2)
Inserting personal experience or values (I)	We came up with the following criterion for our weighted matrix. (I1)
	We tried to find something that we all thought was inconvenient in our life. So that we could improve it. (I2)
Redirecting focus elsewhere (R)	We believe that this mechanism successfully meets all three of our requirements, as indicated by our prototyping and user interviews. (R1)

4.2 Techniques used to communicate design rationale

Surprising elements from the data were the written techniques designers and engineers used to communicate design rationale, coded as making assumptions, inserting self, or redirecting the reader's focus elsewhere. These findings were surprising in that the strategies cited were not objective, using evidence-based reasoning commonly associated with engineering practice. Table 3 shows the frequency of codes and the number of documents the codes appear in of the 28 total documents. These codes further explain how design rationale was communicated in lower levels of clarity.

Making assumptions or generalizations is one technique designers use as justification, most frequently appearing as a summary of entire design stages or as interpretations of their users' thoughts and actions. Two examples, G1 and G2, are listed in Table 4 as representative coded segments. A team working on a wearable that displayed biometric data stated (G1), "*Three metrics were not too overwhelming for the user to look at."* This statement was used to support their decision of three biometric markers to display to the user of the wearable prototype. The breadth of biometric variables that the team could have displayed was vast. The selection of those three metrics was not mentioned. The general statement leads the reader to assume that theories in cognitive load could explain the decision to pursue three metrics. However, this is only one possible explanation a reader might assume, which appears to make sense and sound logical. Another reader might assume the screen size was a limitation—the lack of information results in a wide range of interpretations.

Additionally, a team working to improve remote education for grade school students made the following generalization (G2), *"The stylus is similar to a pencil that students would normally use at school."* The prior statement was mentioned to support the team's use of a stylus and tablet-type design. The design team assumes users' likelihood of using a product based on existing product usage. As a reader, simply because the proposed product is like an existing product, there is no guarantee of product adaptation. If the existing product is too similar, what incentive is there for users to adopt the new technology. The reader's interpretation reflects a poorly supported design decision and questions the design team's credibility.

Inserting personal experience or values to motivate design decisions is the second defined strategy designers use by inserting themselves into the design process. The example I1 from Table 4 is from a team that aimed to improve safety for festivalgoers. Their rationale suggests the team went ahead and decided on design specifications without linking the evidence to their selection of those criteria. Design projects where the problem space is open-ended and to be decided by the team often result in teams deciding to work with users like themselves or solve problems for people like themselves, which is a known issue. Despite the design principle to listen to your users and their needs, designers knowingly and unknowingly insert their experience as representative of what their users want. In a separate excerpt, I2 from Table 4, a team justified their problem space by relying on their personal experience to drive the problem space selection and, ultimately, product solution. By elevating one's experiences over the knowledge acquired in the design process, the design team under explores their design space and closes off different perspectives. Although a design team may be well-intentioned, they are no longer designing for their user but rather for themselves.

Redirecting focus elsewhere means the designers and engineers use references to other pieces of information to support their design features and functions. In terms of clarity, the most explanatory approach includes linking another source of information such as a specifications table, figure, or appendix to their rationale. Next is a designer's allusion to a previous stage in the engineering design process, such as specific user interviews or methods. Lastly, the vaguest usage of this technique can be encapsulated by the coded except R1 from Table 4. The statement mentions an undefined mechanism of the final design, all three requirements are not listed nor referenced in a different section of the report, and a sweeping statement about the design process is used. The statement shows poor communication and questions the credibility of the designer and the rigor of their design process.

4.3 Communication patterns of design rationale were independent of innovation type

An additional analysis of levels of clarity and techniques were segmented by innovation project type, as shown in Table 5. Product-service and spatio-social have a higher average frequency of occurrences than the product type regarding clear communication. Concerning missing information codes, the innovation types are similar (between 22 and 27% on average). Redirecting focus (92 codes) leads as the most common technique used, followed by making assumptions (75 codes) and inserting self (62 codes). Across the assumptions category, the average frequency of occurrence is similar. In contrast, redirecting focus occurs more frequently within the product and product-service innovation types.

Redirecting focus in the system with physical components makes sense because of their physicality, but when reviewing the code segments within the redirecting focus code set, the segments often allude to other documents or processes like interviews or specification guides. The analysis of project innovation types does not reveal noticeable differences across types. Therefore, the challenges in communication are observed across the board, independent of innovation type.

TABLE 5: Breakdown of the number of coded segments per code set and split by project innovation type. Product type contains 13 projects and 203 codes. Product-Service contains seven projects and 133 codes, and Spatio-Social contains eight projects and 122 codes.

Code set	Product	Product-Service	Spatio-Social
Communicating Clearly	41 (20%)	37 (28%)	38 (31%)
Missing Information	54 (27%)	33 (25%)	27 (22%)
Making Assumptions	33 (16%)	23 (17%)	18 (15%)
Inserting Self	31 (15%)	12 (9%)	19 (16%)
Redirecting Focus	44 (22%)	28 (21%)	20 (16%)

5. DISCUSSION

Written communication is one form that engineers and designers use to communicate design rationale. The results were extracted from an exploratory qualitative research process which identified three main findings. First, this research shows that design rationale can be thought of in clarity levels, with explicit design features, specifications, and evidence to support those specifications serving as the most precise form of communication, as defined in this work. In contrast, the lowest level of clarity includes written communication of design rationale that is missing parts of this design rationale framing or rationale altogether. The second finding presents three observed techniques designers use when communicating design rationale. These techniques can be used independently of the levels of clarity. The last finding describes the influence of project innovation classification on communication, which appears negligible. Combining these findings highlights the variety in design communication and some of the written strategies designers lean on. The following sections outline the implications of these findings, practical methods to improve designer communication, and applications of these findings within human-AI collaboration.

5.1 Implications of communication clarity on designer credibility

The three techniques observed are used on varying levels of clarity. Upon first summarizing the results, the emerging themes appeared when part of the rationale or the entire rationale was missing. These techniques were also used by designers and engineers who communicated clearly. Therefore, the following techniques lead us to believe that when designers make assumptions and communicate clearly, they have knowledge about their users, which influences their decisions. Rather than extract the meaning from interviews with direct quotes, the designer states that the designer prefers this prototype. Situations where designers insert themselves or their values show they are trying to fill the gaps to the best of their knowledge and experience.

The last technique noted that occurs in poor and good communication involves redirecting the reader's focus. One might use the redirect to provide a clear visual representation of the finished prototype they are discussing and link it flawlessly to the feature or attribute described. Alternatively, other teams' redirection leads us to assume they do not know why they completed said design actions nor how it influenced decisions. The redirecting technique led us to believe that they want their reader to know how much work they did. This show-and-tell approach removes the focus from the user and toward the design team's achievements. By doing so, designers cannot identify the critical aspects to articulate and prematurely believe every step they take needs to be shown. Previous research on technical writing has found that complicated sentences, lower accuracy, and less organizational structure (often in student's work) resulted in decreased effectiveness in areas that practitioners in engineering considered important (e.g., accurate and unambiguous content; fast, predictable reading; liability management; and attention to detail) [34]. A lack of organization and clarity shows their inability to express engineering content effectively.

A lack of documented design rationale does not necessarily indicate the team used no rationale. Instead, the absence or fragmentation of design rationale points to a team's subpar ability to communicate, or perhaps more interesting is a team's use of these explanatory crutches as mentioned in Section 4.2. The absence of the design rationale may not necessarily be alarming. Instead, the implicit design rationale could suggest a team has a shared cognition or mental models of their design actions and motivations [35,36]. Since each student was involved in the entire process, they might have a higher shared understanding of the information guiding their team's decisions, which could explain the lack of clear design rationale in the technical reports used for this research. However, the shared understanding may no longer hold moving beyond the immediate design team, requiring explicit design rationale to be stated. More detailed design explanations would be expected when less information about the design challenge and solution is known.

Prior literature has identified technical professionals' challenges in communication [1,16]. The lower levels of clarity as outlined in this dataset could be attributed to this natural occurrence. However, there are likely additional explanations. A more cynical explanation could be attributed to a team's lack of logical reasoning resulting in the team using the techniques described above manipulatively. Thus, while they may appear to communicate design rationale, they insert their personal experiences or redirect the reader's focus to find the rationale in another portion of the document (that may or may not exist). Due to the short project nature of the design courses, which lasted a semester or summer, the rationale for their design decisions may be unknown since they did not have sufficient time or resources to support their decisions [37,38]. Rather than state these uncertainties, they appear as missing information via the techniques highlighted. Designers respond differently to uncertainty; some are motivated to engage with uncertainty and resolve the uncertainty, while others favor familiarity [39,40]. The teams may be using the techniques to favor what they already know (e.g., personal experiences) or to avoid grappling with the uncertainty in their projects.

5.2 Practical approaches to improving design rationale communication through reasoning frameworks and intended audiences

The first approach to improve design rationale communication and documentation might consider using traditional reasoning frameworks. The philosopher, Charles S. Peirce, identified three types of reasoning, deductive, inductive, and abductive reasoning [41]. Each of these classes is composed of a rule, case, and result. Deductive reasoning involves using existing knowledge to draw guaranteed conclusions. Meanwhile, inductive reasoning states that a conclusion is likely. Then there is abductive reasoning which assumes the best-case scenario solution. Table 6 shows an example for each reasoning group.

TABLE 6: Logical reasoning examples from [11].

Reasoning	Example
Deductive	Because GPS do exist today and we have seen this sort of stuff existing already, so it's not a completely new idea, I guess.
Inductive	We're so lazy, that anything that saves us walking up to switch the light switch on and off is everyone's.
Abductive	But you can also use it for like busy people for terminal disease or something like that.

Research from Summers made clear that reasoning in design includes all three reasoning types [41]. Pierce's traditional logical reasoning classification has been used to code protocol studies, and each form of reasoning is present within the design process [6,42–44]. We wanted to expand beyond simply classifying reasoning within the design process and instead show the breadth of communication strategies designers and engineers use to communicate design rationale. The effectiveness of the clarity and techniques observed require further insight to quantify their influence on design decisions and outcomes.

Most engineers and designers know deductive reasoning but do not know the meaning of inductive or abductive reasoning [45]. Hernandez developed an engineering reasoning-based course in which logical reasoning was introduced with the goal of increasing scrutiny of the final design and justifications [46]. A follow-up investigation into the reasoning-based course and its impact on design rationale communication could be considered. Moreover, reasoning in engineering design teams in industry has been studied to improve the transfer of knowledge and project documentation by introducing and implementing design rationale capture tools and frameworks [47–49]. By incorporating standards to document design rationale, project organization improved, and contrary to expectations, designers found such a system natural and helpful in their communication processes [47].

In addition to using logical reasoning frameworks or existing knowledge transfer systems, designers and engineers should know their intended audience. Therefore, engineers can write and position the document to best serve the intended stakeholders [50]. The document's purpose can vary in industry depending on the stakeholder (i.e., one for the business side, internal design team communication, external to technicians). For the scope of this research, the data sources were end-of-term design reports, and the intended audiences were instructors. The reports were meant to stand alone since the instructors had no more opportunities to ask follow-up questions once the semester finished.

Improving communication within engineering design will help with the study of and collection of design rationale. In our study, students were not explicitly primed to detail their rationale but rather a synopsis of their design process. In most of the reports, detailed rationale was absent. A future study might explicitly instruct participants to document a design decision and corresponding rationale. Educators may want to consider implementing reasoning frameworks, knowledge transfer systems, or asking students to write for a specific audience. Each approach would help engineers and designers identify what they should be communicating and how they should be conveying that information when documenting their design process.

5.3 Applications for levels of clarity and techniques within human-AI collaboration

The results show that design rationales were not always communicated clearly, and the techniques used varied. Shared knowledge within a team could explain why design rationale was missing. However, human-AI partners may not have this shared knowledge. Current AI systems struggle with explaining why they perform their actions aside from replicating human behavior [25,51]. Implicit design rationale might arise from domain expertise, common sense, or bias. The ability to explicitly link implicit design reasoning to design actions as defined in communicating clearly would benefit the development of explainable design agents. More specifically, future work should consider applying the findings (levels of clarity and techniques) to help classify the design rationale provided in written documents. These classifications can evaluate the effectiveness of communication or the strategies used to help determine viable texts from which clear design reasoning can be extracted. By segmenting design rationale, future work could better understand the influence each grouping has on design decisions and outcomes.

Within engineering design, previous research has shown several advantages to introducing AI design agents to assist human designers at various stages of the design process [52–55]. Research from Raina et al. used deep learning to imitate human designers where the system performed just as well or outperformed human designers. However, the rationale behind the agent's decisions remains unknown [25]. Although the system may objectively recommend a higher-performing design, the consideration and ideally acceptance of the agent's recommendation relies on the agent's ability to explain its rationale. Research suggests that AI recommendations should be simple for designers to understand [51]. Ideally, the decision-support tool should explain its design rationale to supplement the design recommendations it is making. This ability to explain design rationale informs trust and influences a designer's decision.

Depending on the explainability, or levels of clarity as defined in this study, designer confidence in a decision-support tool will vary [51]. Previous research in autonomous vehicles has shown that communication style and the level of information provided influenced a human's trust in the system [29]. Within human-to-human interactions, previous research from Dong et al. showed that the logical framing structure (i.e., abductive, deductive) significantly influenced design decisions [11]. Deductive reasoning was more likely to cause human participants to reject proposed designs, whereas abductive reasoning was more likely to accept a design product or feature. The findings from this research show a wide range in how design rationales were documented, and thus a wide range in human trust in an agent's recommendation should result.

5.4 Reflection on methods

The data sources for this work involved course design deliverables from 14 teams in a graduate-level course and 14 reports from two undergraduate courses over two summer semesters. Due to the varying levels of expertise and domain knowledge, further analyses of this topic and how expertise influences design rationale could be considered. The reports selected for analyses were from students (i.e., novice designers) and thus would likely differ from industry reports. The differences between teams and companies in industry would also vary in their communication expectations. Researching design rationale in industry documents will be explored in future work. Although design rationale and its components were defined in this study, the level of detail necessary for understanding a system, feature, or function was not defined. Some teams included complex finite element analysis to support their decision, while others described the rationale at a high level without providing a detailed breakdown of the information and process used. Would one method be preferred, or is the degree of detail dependent on the shared knowledge between the designer and reader of the technical report?

The research materials and methods used in this research were evaluated according to the measures of confidence and relevance by Atkinson et al. [56]. Each step of the qualitative process and codes, integration work, and memo-writing are documented via MAXQDA, lab notes, and Mural. Concerning triangulation and reflexivity, students in the design courses were unaware of the researchers' presence. The reports were received after the completion of the courses. In the analyses, any identifiers were removed before the coding began.

Regarding corpus construction, the design deliverables were a convenience sample from some of the previous courses members of the research group instructed. In terms of thick description, direct quotes are used in the results and discussion. They are linked to the relationships of levels of clarity. The element of local surprise arises through the degree of impartial or missing design rationale in final design deliverables. Analyses of these missing and impartial rationales highlight techniques designers use to fill those gaps. The main takeaways regarding levels of clarity and techniques are mentioned in detail in Section 4. However, future work will consider communicating validation using the code sets on new data sources to verify the prevalence of the emergent themes.

6. CONCLUSION

Engineers and designers need to provide design rationale when creating products and systems. Design rationale goes beyond stating the intent of a product feature or function and links together that feature or function with a design specification and information used to define that requirement. This research aimed to understand how engineers and designers communicate design rationale in written technical design reports. Eight hundred and forty-six pages of technical design reports were collected from three project-based undergraduate and graduate engineering design courses. Using a mixed-methods approach, these reports were analyzed using thematic analysis inspired by the grounded theory process, and the emergent themes were visualized for their relationships to one another and frequency in occurrences. The main findings include a broad range of how design teams communicate design rationales. The clarity levels suggest a designer's inability to articulate their motivations or a lack of understanding behind their teams' or individual's design decisions. Techniques such as making assumptions, inserting oneself, and redirecting focus, were three strategies commonly used when rationale was missing information. Depending on the use of or lack of design reasoning framing, the range of design rationale identified in this research likely impacts trust and resulting decisions. The implications of this work highlight the gaps in communication of design rationale and a classification scheme in which clear design rationale can be extracted for use in design support tools.

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