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Exploratory analysis of a crowdsourcing metadata tool for building terminological consensus in civil engineering

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ABSTRACT

The longstanding absence of common terminology across the Architecture, Engineering, and Construction (AEC) industry results in communication barriers and hinders smooth collaboration among professionals across these disciplines. To address this challenge, the potential of a crowdsourced methodology was investigated in this paper to assist in improving terminological consensus using an online platform: Yet Another Metadata Zoo (YAMZ). Participants from the academic form-finding community were engaged to interact using YAMZ. Definitions, comments, and votes were collected and analyzed to understand their quantitative and qualitative relationships. The results indicate that a crowdsourcing methodology can be employed in research groups to build terminological consensus and may enhance research through improved terminology production. Addressing each of these challenges could help reduce semantic ambiguity among stakeholders in AEC projects. It was concluded that a crowdsourced approach may offer a pathway for faster standards development, although a broader study involving stakeholders from the AEC field is necessary.

1. Introduction

Science and engineering rely upon precision in measurement and instrumentation to arrive at sound, verifiable conclusions; although, expressing such ideas in everyday or a technical vernacular can introduce ambiguity. These challenges stem from shifts in language usage and disciplinary silos to personal idiosyncrasies. To overcome such issues, standards bodies such as the American Society of Civil Engineers (ASCE) [1] have developed terminologies to provide a common linguistic ground. Unfortunately, terminology development often takes a long time and reflect dominant trends or schools of thought in a field. As a result, terminology may be outdated and nuanced or non-dominant usage might be overlooked or omitted. These challenges are amplified in interdisciplinary and transdisciplinary fields such as architecture, engineering, and construction (AEC).

Terminologically, civil engineering (CE) not only relies upon the language of engineering but also must convey aspects of design and implementation. These issues come into greater distinction among interdisciplinary teams when members use identical acronyms with different meanings, e.g., FDM — fused deposition modeling (a method of 3D printing) [2], force density method (a numerical form finding method) [3], finite difference method (numerical method to solve differential equations) [4]. The use of identical words with different meanings, in this case, also impacts communication across disciplines, as in the case of "tectonics", which in architecture means the structural function of a building [5], while in geotechnics, it addresses the plates in the Earth's crust [6]. The case of FDM displays homonymy while that of tectonics, polysemy, each of which increases the potential for linguistic ambiguity.[2]

Many researchers have emphasized the need to build a common ground across AEC disciplines [7]. This demand is accentuated by the acceleration of data-driven research due to, for example, incompatibility of terminology between software used in different stages of an AEC project [8,9]. Social media environments may offer a solution here, particularly platforms that support collaborative work and enable community dialogue. Research is needed to test and demonstrate how collaborative vocabulary development would work in AEC. The research presented in this paper considers this need and demonstrates how a collaborative vocabulary tool might assist civil engineers in

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2 Homonymy is the case where identical words have different meanings based upon different etymological origins, while polysemy is the existence of multiple meanings for a single word whose root is the same.

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a subset of the academic form finding community's vernacular use of terminology. To pursue this work, we selected YAMZ [10], a tool that allows users to define, comment, and vote on terms in a fashion similar to Stack Overflow [11]. Furthermore, YAMZ allows for users to choose and link to a preferred definition even if it has not received the most votes. The system has a low barrier of entry for use. The crowd-sourced methodology implemented by YAMZ can also bridge disciplinary knowledge gaps, permitting more effective interdisciplinary data sharing. In addition to these factors, the tool implementation simplifies text and voting data collection for researchers. This study explores the current tool functionality and extends prior work on YAMZ. Greenberg et al. [12] engaged a small pool of users in an informal setting. The present work expands both the user pool and timeframe for data collection, allowing for a limited but more insightful view of terminological differences among participants.

1.1. Organization of the present work

We organized the present work into five sections, as follows. We survey the literature in the present section (Section 1), including an overview of the challenges in building terminological consensus from the perspective of both AEC (Section 1.2) and information science (Section 1.3) disciplines. We provide materials and methods required to conduct the study in Section 2. We present the study outcomes and data in Section 3, with discussions of those results in Section 4. Section 5 summarizes our findings, concluding the present work and points towards future research directions.

1.2. Civil engineering terminological consensus-building challenges

CE, especially as it relates to building construction, presents several vocabulary challenges [8,13–15]. The first of these is transdisciplinary communication. Professionals in AEC communicate through specialized vocabularies to convey messages inside the same project. Each interaction between disciplines includes a vocabulary for the "translation" of technical terms from one team to another. This section introduces categories in the AEC disciplines that have presented formal settings to develop and build consensus for technical terminology to date. These categories are: (1) definitions of new terms in research groups, (2) composition of terms in glossary sections of standards, and (3) standardization of terminology in digital workflows. Each category has well-established processes to provide terminology definitions as described in the present section. Section 4 discusses the application of the tool presented herein to these categories.

1.2.1. Definitions of new terms

In this section, we identify how new terms arising from research are defined and how they propagate into publicly available text and widespread usage. Section 4 argues for the use of the method and tool presented herein to the early stages of this process.

Research groups often coin terms that summarize a newly developed concept or method. The terms for these new concepts and methods undergo modifications and development through sustained usage and publication. Researchers outside the discipline may also alter meaning or context of a term. A stable dictionary definition often captures the more generalized form and meaning. The term *4D printing* exemplifies this process. This term was coined to explain or shorten the concept of 3D printing with time-dependent properties. Instead of writing about a (3D printing technique that) "(...) entails multi-material prints with the capability to transform over time, or a customised material system that can change from one shape to another, directly off the print bed" [16, pp. 119], the new method is simply referred to as 4D printing. As the term spread from the field of architecture to other fields, it evolved and encompassed the terminology and broader scope of material science [17], bioengineering [18], and chemistry [19].

The term was eventually included in the Oxford Languages dictionary as "the action or process of using 3D printing techniques to create an object that is able to change its shape or properties in a predictable way over time in reaction to conditions such as exposure to water, air, heat, or an electric current" with the example: "add a time dimension and energy source to 3D printing and you have 4D printing" [20]. As the 4D printing process spread, there was less need to identify the uniqueness of the materials used. Another discussion on the same term occurred in [21]. There, 4D printing is defined as "the 3D printing of an object from smart material that is programmed to predictively change its properties, grow in size or mass, or generate chemical spawn in response to stimulation" [21]. The authors of [21] considered this definition to include all processes that should be considered 4D printing which are reviewed in the publication.

The example provided by the term *4D printing* shows how the definition of the term not only evolved in time but also how the term has certain nuanced definitions depending on the field of research in which it is employed. Moreover, the example shows a progression from coinage to regular usage to a standardized term. Simultaneously, that example shows the reduced usage of a qualified form of 3D printing.

1.2.2. Glossary sections in standards

In this section, we examine how new technical terminology is developed to enter glossary sections of standards, design guides and primers. In Section 4 we argue for the use of the crowed-sourced method to formalize a discussion space for terminological definition in early development stages of design guides and primers.

Standard-making processes follow a rigorous peer-review procedure, as well as compliance assertion to previously published standards to avoid contradictions among different volumes [22]. Research results included in standards are likely to have undergone years of study by multiple research groups. Therefore, the technical terminology included in standards largely includes terms with less volatile definitions. Certain terms, such as "loads", include a general definition in the introductory chapter [23, pp. 1], and later include definitions for different types of loads in subsequent chapters [23, pp. 11]. The definitions of types of loads may suffer more updates compared to the general definition [24, pp. 33]. The term "loads" is also an example of a term with a coordinated definition with other standards development organizations [25, pp. lvii] as it has a commonly accepted definition across different CE disciplines.

The highly coordinated and rigorous process of including terminological definitions in standards can be contrasted to ASCE's technical report-making process and ASCE Press publications which include primers and design guides. Technical reports offer a more flexible approach because they are intended to present the use of state-of-the-art research and CE industry developments [22]. ASCE Press publications such as primers include peer-reviewed thought-provoking books to contribute to the technical body of knowledge for engineers [22]. An example is "The Engineer's Project Delivery Method Primer: Uniform Definitions and Case Studies," [26]. This publication provides a table of definitions to address nuances in technical terminology. This primer is not designed to capture vocabulary differences for all situations and exemplifies the need for tools directed to give the community control over vocabulary nuances—a place where each group can clearly state: "When we use this term, this is what we mean." Gransberg et al. [26, pp. 55] notes the terminological complexities found in projects which arise due to differences in regulations and laws subject to particular geographic regions.

1.2.3. Standardization of terminology in digital workflows

In this section, we identify how digital workflows are often built with different vocabulary and, when files from different software are combined, compatibility issues arise. We argue in Section 4 that collaborating interdisciplinary teams could use the crowd-sourced methodology to agree upon terminology prior to model implementation to reduce incompatibilities.

The first aspect of this category is that terminology can be developed through collaborative means such as YAMZ or wikis as well as through automatic term extraction [27] which allows for machine learning algorithms to locate terms with specific usages from a large corpus of documents. Each of these methods circumvents the need for extensive expert review and can build upon or augment prior efforts of standards bodies. Moreover, terminologies in digital workflows are often used for categorization efforts for data-driven applications [28] or else as backbones for knowledge graphs supporting artificial intelligence efforts [27,29,30]. Terminology for such applications is often developed under highly specific circumstances to support a specific area, and this can lead to possible further siloing of information.

In digital environments, interoperability between different semantic systems facilitates workflow integration across different disciplines. At granular levels where terminology is often highly specific, mapping terms across structures ensures that researchers are referring to the same concepts reducing terminological ambiguity. This topic is extended in the subsequent Section 1.3.

1.3. Knowledge organization systems

Constructing effective methods for classifying information relies upon the development of applicable syntactic and semantic structures. Semantics primarily concerns itself with meaning and structures which convey the different relationships ranging from basic word lists to complex taxonomies and ontologies. These structures all rely on shared vocabularies that allow for mutual understanding across applications and disciplines. Such vocabularies range from informal to formal, which denotes their level of control over terminology often by a standards body, e.g., a formal, controlled vocabulary might be how information is presented in official documents, but often in papers or everyday speech informal usage prevails. Formal, controlled vocabularies are often developed according to a set of disciplinary information needs as well as a set of rules governing their linguistic representation, such as the ANSI/NISO standard, "Guidelines for the Construction, Format, and Management of Monolingual Controlled Vocabularies" [31]. Such guidelines tend to be intricate and focus on the dominant usages and can inadvertently fix meanings due to the time and monetary commitments necessary to develop them. Terms and definitions are generally defined based upon their usage in literature, i.e., literary warrant [31]. However, other forms of usage, such as how users engage with information (user warrant) or expert opinion (academic warrant), can similarly justify terminology [32].

Collaborative vocabulary systems approach shared terminology as a "bottom-up" structure where users develop the basis of terminology from personal understanding or practical usage as opposed to the formal, "top-down" vocabulary developed by experts. Collaborative systems originated in the branch of human–computer interaction research called computer-supported cooperative work. Chen [33] describes one of the first platforms for collaborative vocabulary based in the worm biology community. Chen's [33] concept space allowed for users to interact, and from the comments and discussion, terminology was mined. With the introduction of Wikipedia in 2001 [34] collaborative knowledge bases have reached a much larger audience. Wikipedia allows for collective editing of entries and maintains version control of textual changes and updates. The wiki structure has given rise to variants such as MediaWiki and Semantic MediaWiki. This latter incarnation of the wiki structure was implemented by Jaykumar et al. [35] to develop a collective vocabulary tool called KnowledgeWiki which was specifically designed for materials science. Semantic MediaWiki technology facilitates semantic web metadata, allowing for more precise connections in linked open data. An alternative approach to crowdsourcing terminology is provided by YAMZ which differs from other platforms by providing a framework for voting on terms. Prior work on YAMZ [12] has focused on user engagement of terminology in the materials science space. The present work expands upon the demonstration initiated in [12]. As a crowdsourcing tool, YAMZ leverages individual users' practical expertise to develop a meta-vocabulary which can contain a variety of comparable definitions across a wide range of disciplines.

In AEC projects, participants derive from a diverse range of disciplines. Ensuring that the various information environments connecting these participants in project processes such as Building Information Modeling (BIM) is paramount [14]. Terminology developed through crowdsourced means such as YAMZ or wikis allows systems from different areas to translate more accurately users' concepts and meanings increasing the semantic interoperability. While semantic interoperability among highly specific areas might be more difficult to obtain, communication between disciplines is necessary for projects that, for example, use BIM processes and tools that rely on computational modeling compatibility. This is especially important when constituents come from different backgrounds but have a common goal, i.e., a completed structure.

1.4. Research questions and study aim

The aim of this study is to explore how a collaborative definition tool can possibly aid civil engineers to build terminological consensus. A separate goal of this study is to act as a pilot for a larger study. To conduct this analysis, we investigate two guiding research questions: (1) How can professionals in the AEC disciplines, specifically in a subset of the academic form finding community, produce more consistent and insightful terminology? (2) How does a methodology implemented in a tool like YAMZ assist in better terminology production, and how can we characterize user engagement?

2. Materials and methods

In the present section, we first show how terms were selected and the user pool for this exploratory analysis of YAMZ. Then, we elaborate on how this study was structured and conducted. The data analysis method is also provided. The flowchart in Fig. 1 summarizes the method for this study. The method includes: (1) a pre-study phase including term and user selection with subsequent term distribution to users; (2) a study phase encompassing the use of the crowd-sourcing tool YAMZ; and (3) a post-study phase with qualitative and quantitative assessment of the data collected from the study.

2.1. Term selection

A set of thirteen terms related to the area of form finding was selected and divided into three categories: (1) recently coined terms with definitions established in journal publications within the last decade (n = 3) with relevance to the participants' research, (2) terms with well-established dictionary and text-book definitions but with possible nuanced or particular use within the group (n = 5), (3) trending terms with dictionary definitions used with unclear definitions by the broader research community (n = 5).

The first category of terms allows users to catalog recent terms relevant to their research. It is common for researchers to coin terms that summarize a new concept that is lengthy to use repeatedly, as identified in Section 1.

The second category consists of terms widely accepted in engineering practice and academia whose definitions can be found in books and technical standards and are also often used with slight variations or with particular meanings within a research group. The intent of including this category of terms was to allow users to provide more specific or idiosyncratic usages in contrast to the broad or standardized definitions provided by textbooks and dictionaries.

The third category of terms included those used in presently trending topics. This category includes terms with a formal definition widely accepted by the research community. However, the term may have

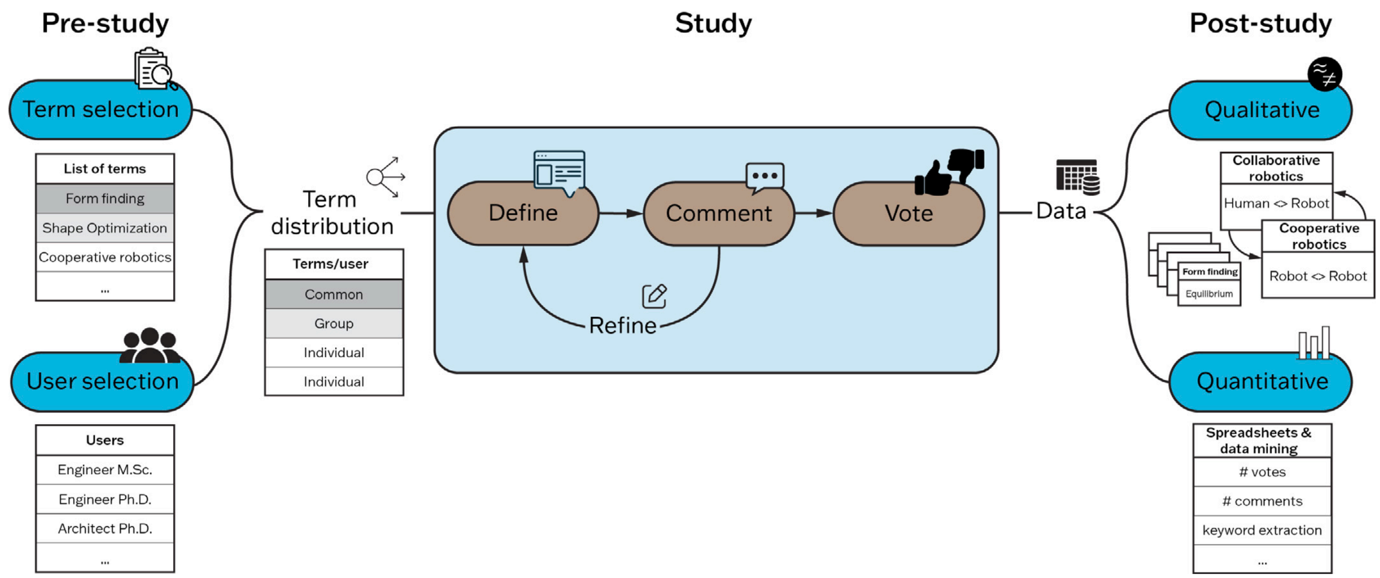

Fig. 1. Flowchart specifying the method of this exploratory analysis.

Table 1
List of terms with definitions provided by users.

	Term
1	Form finding
2	Shape optimization
3	Inverse design
4	Boundary conditions
5	Loads
6	Self-supporting structure
7	Structural design
8	Structural detailing
9	Internal forces
10	Cooperative robotics
11	Collaborative robotics
12	Fabrication-informed design
13	Tectonics in architecture

been loosely used in informal settings to describe other processes, and the term loses its original precise meaning, possibly creating ambiguity on how it is deployed. Including this category allows users to move current debates on what these terms mean from informal group discussions into a formalized space (YAMZ), where the definition can be used later for reference by a broader audience. The terms are listed in Table 1 and the peer-reviewed published definitions are listed in Appendix. Terms 10 and 11 have been used interchangeably in the literature and therefore have the same entry in Appendix.

2.2. User pool

The user pool includes a targeted group of researchers in the form finding community primarily chosen for convenience and known expertise. Form finding generally presents semantic challenges that operate at the junction of different disciplines and professions, such as architecture, structural engineering, and digital fabrication. Not all lab members participated in this demonstration, and not all participants had academic collaborations with lab members. The set of invited users was meant to reduce the chances of any identification. The convenience sample [36] was used to ensure that participants met the baseline criterion to establish expertise in the field: enrollment in or completion of a graduate degree in civil engineering or architecture. The user pool included nine people out of thirteen who were invited to participate. Credentials among this user group broke down as follows: 33% had completed a doctorate; the remaining 67% were graduate students; and 78% of the entire group had published in the field of lightweight structures. This user pool represents a threefold increase in participants over a prior study involving YAMZ [12]. Anonymized usernames were distributed among participants to reduce the risk of user identification within or without the group, as well as by the researchers while analyzing the data.

2.3. Structure of the exploratory analysis

The application study was designed to be conducted within a week, which was extended by one day. The requested time investments from each participant were suggested as half-hour sessions on three to four different days within the span of a week.

The participants were introduced to the tool and the study objectives on the first day of the week. The introduction included a tutorial session on how to use YAMZ. The email instructions were sent on the same day to each user with the tutorial instructions, the terms for them to define, and the randomly generated username.

The participants were instructed to contribute definitions and examples of the provided terms on the second and third days of the week. On the fourth and fifth days, they commented and voted on other users' definitions. They were instructed to comment on at least three other terms. Finally, one additional day was given for users to provide rebuttals to the comments on their definitions.

While the initial design of the YAMZ exploratory analysis included five weekdays, the study time was extended by one day, allowing users to provide additional comments and rebuttals. Table 2 shows the implemented timeline, where the shaded boxes indicate the planned experiment, and dots indicate tasks as executed. Voting days were suggested but since timestamps are not recorded for votes, the actual time of execution cannot be provided. To keep users engaged in the study, an email reminder was sent every other weekday regarding the stage of the study. Users were guided to provide definitions on the first and second days, but some users provided a definition on the third day of the study, and one of the definitions was provided on the fourth day. This flexibility allowed for more people to join the study, but it also reduced the chances of the definitions provided on the third and fourth day being commented upon by other users.

2.3.1. Term distribution

All terms were pre-selected and assigned to users through individual e-mail communication. All users received a set of three terms to

Table 2
Timeline of the structure of the study.

Task	Day 1	2	3	4	5	6
Instructions and tutorial	•					
Define	•	•	•	•		
Comment			•	•	•	•
Vote						
Rebuttals						•

define and one additional optional term. In total, twenty-one terms were distributed to thirteen invited participants. From the twenty-one terms, one term was assigned to all users. Three terms were assigned to three groups of users and each user participated in one group only. The remaining terms were distributed to users individually as required or optional terms. This distribution allowed researchers to collect information on different categories, as described in Section 2.1.

2.3.2. Definitions and examples

Users were asked to provide a definition and example for each of their list of terms. No specifications were placed on how users could define terms or the examples used.

2.3.3. Commenting and voting

Participants were finally asked to comment and vote on terms other than their own. It was permissible for users to perform both actions simultaneously. Users could also use the comments section to rebut or clarify other users' comments. Voting occurred anonymously, a feature of the YAMZ application.

Limitations in both the study and YAMZ does not preclude the possibility that users may have accessed others' definitions prior to providing their own. It was communicated to the users that the definitions would not be judged regarding correctness. Rather, we aimed to explore the tool's usage by the group of researchers in civil engineering. The study was performed using the current, live instance of YAMZ, and not a test or experimental one, resembling the actual user experience where individuals might build upon, improve upon, or differentiate their definition based upon other user's attempts.

Fig. 2 shows how to enter a comment on an existing YAMZ entry. This figure shows an example of a form finding definition presented at the tutorial session on the commenting and voting page. In Fig. 2, the circular tag 1 shows the first step each user takes in the study phase: to define one of the provided terms. After each user provides their own definitions, they, then, comment (tag 2) on other's definitions. Once the user has commented, the entry cannot be edited or deleted. The users, then, up- or down-vote each term (tag 3). Finally, the users can review the comments left on their definitions and they can choose to edit (tag 4) their initial contribution.

2.4. Data analysis method

Upon completion of commenting and voting, data regarding all pertinent aspects was manually collected into three spreadsheets that focused on each of the facets involved in the study (see Table 3). The first sheet coordinated terms, definitions, and comments. The second connected terms, definitions and voting data. The third sheet isolated each user-generated textual element (definitions, examples, and comments) by user and the comments were assigned a qualifier. Qualifiers were added to differentiate the type of comment: initial, reply by creator of definition, and reply by others. Similarly, comments were categorized based on how they connected to definitions or examples. Comments which exceeded a single sentence and referred to terminology present in either the definition or example we considered substantive. Comments which were a single sentence or phrase but referred to the example or definition were flagged as less substantive. And comments which were generic or thanking another user were

Table 3
Data organization and separation into three spreadsheets.

Spreadsheet	Contents
Term data	• Definition • Example • Published definition • Term group • Matching score • Comment (1, 2, 3, …) • Commenter (1, 2, 3, …)
User data	• Contributor or Commenter • Content type • Content qualifier • Content (Definition, Example, Comment)
Voting data	• Score • Aggregate vote • Up vote • Down vote • Magnitude vote • Definition • Example

classed as non-substantive. These categories are not meant as value judgments of comments but rather speak to length and overlap with the associated definition or example.

The unique Archival Resource Key (ARK) [37] assigned to each entry was used to disambiguate identical terms and correlate data across the different sheets. In addition to ARKs, each sheet connected textual elements to the appropriate contributor's user name. Throughout this work, the ARK reference, in the form hXXXX, where X represents an integer, will be provided for the referenced terms.

Researchers split the voting data into several distinct categories. Upvotes for a term received positive values while downvotes received negative ones, and the aggregate vote value was the sum of the upvotes and downvotes. Magnitude of voting measured the sum of the absolute values of upvotes and downvotes, providing a metric which showed overall degree of voting engagement with a term. YAMZ scoring is a related value, discussed in [38], which provides a weighted version of the voting based upon community contributions of definitions, comments and votes. Scoring results were included in the data set because they feature prominently on the YAMZ platform and determine a term's status as either vernacular or canonical, but they do not figure significantly into the current analysis because status changes did not occur during the course of the demonstration.

Definitions were also ranked from one to five matching scores compared to definitions in peer-reviewed publications. Matching scores are not used to judge a definition for correctness but only as a metric of similarity to the published definitions identified by the authors of this study as included in Appendix. Scoring criteria for each value are as follows:

1. The user's definition provides an interpretation of the word that contradicts the published meaning.
2. The user's definition includes examples similar to the peer-reviewed definition but does not match the peer-reviewed published definition.
3. The user's definition matches the published definition partially.
4. The user's definition matches the published definition up to 90% of the content. There was either a minor concept left out from the user's definition in comparison with the published definition, or the user's definition provided additional information that was included only in the examples of the published definition, making the user's definition too specific in comparison with the published definition.
5. The user's definition matches the peer-reviewed definition's contents exactly.

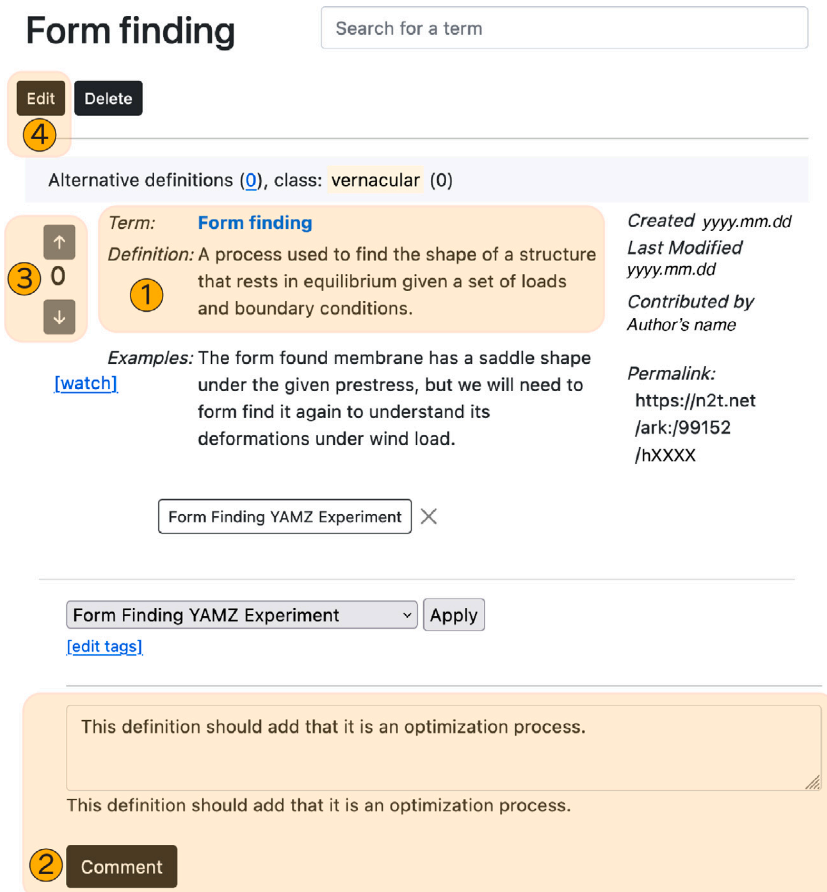

Fig. 2. A window showing the YAMZ tool where users can: (1) define a term; (2) comment; (3) vote; and (4) edit their entries.

The collected and coded data were then analyzed using qualitative and quantitative methods to locate trends among the sample. Content analysis examined possible interactions between the different fields specifically comparing the semantic similarities and differences between user's definitions and examples as well as how comments were applied to definitions and examples, comparing word frequencies and textual aspects. The Orange Data Mining application [39] allowed for further analysis of text elements, which included preprocessing and document scoring of various textual elements. The limited sample size of participants constrains the depth of analysis and the claims that can be made.

3. Results

Nine out of the thirteen researchers invited to the demonstration contributed definitions. Of the twenty-one individual terms distributed, users defined thirteen of them. Seven out of nine users provided a definition for the single term that was distributed to all users. At least three users from each subgroup provided a definition for the subgroup terms. Definitions ranged in length from 12 to 133 words. Examples ranged in length from 9 to 160 words. In addition, we received 51 total comments on 23 terms. Users could also use the comments section to rebut or clarify other users' comments, but this was limited to 6 instances out of 51 total comments. For voting, 22 terms received at least one vote, and one term received magnitude of 5 votes. None of the terms which received no votes overlapped with terms which received no comments.

3.1. Connections and correlations

The data offer a range of connections based upon comparison of descriptive characteristics present. One area of exploration was between voting data and comments. Voting, as an action whether affirmative or negative, plays a central role in YAMZ, and to account for this activity, the magnitude of votes for each term was considered. Among the 10 terms which showed the most voting activity, commenting, another index of user engagement was analyzed. Among these terms, the comments showed little variance statistically, with a mode of 2 and a mean of 3 comments. Only two terms had more than 3 comments, h8076 and h8089. Of these, only h8076 is correlated with a slight increase in voting, with a magnitude of 4 votes. Conversely, among the 6 terms which received no votes, all received at least one comment which indicates some engagement with the definitions provided (see Table 4).

3.2. Statistical analysis

The descriptive statistics for the data in Fig. 3 present a low-level look at the data. While the definition and example word counts have high maximum values, 122 and 160 respectively, the graphs from Fig. 3 show that the distribution is much closer to the minima for each category, which is borne out by the descriptive statistics. For the definition, median = 29 and mode = 21, and for the examples median = 22 and mode = 20. The proximity of these values shows that the most common values fall closer to the central point of the data.

3.3. Semantic analysis

When considering the meaning behind each provided definition, several observations arise. *Cooperative robotics* and *collaborative robotics* are two terms that are used interchangeably in the literature [40,41] although this fact is not directly stated. Both terms were defined nearly identically in two YAMZ entries—*cooperative robotics* (h8073)

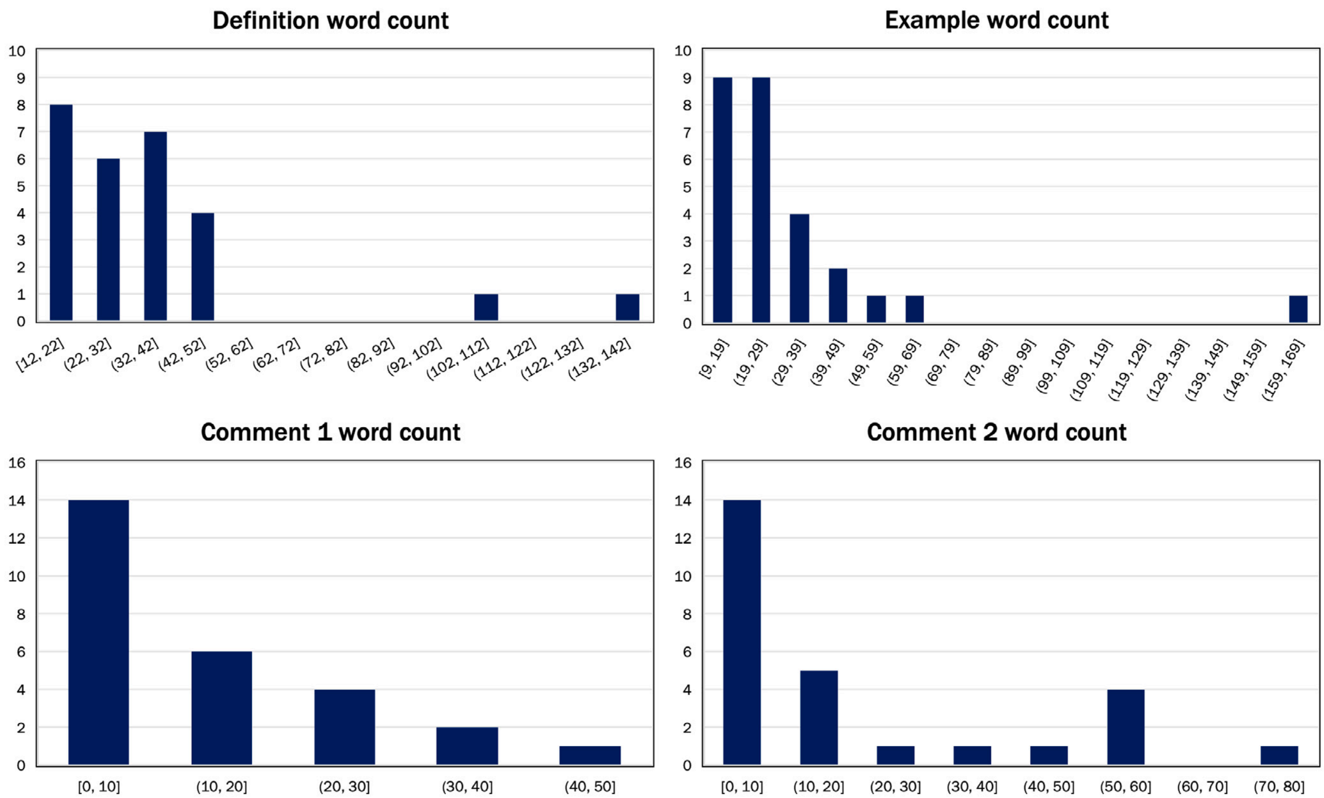

Fig. 3. Word count for different types of entries in YAMZ.

and *collaborative robotics* (h8074)—and both entries sparked the same comments. However, the two terms were never directly related to one another in the definitions or in the comments section. One distinction between the two provided definitions occurs where the author notes a human element in *collaborative robotics* which is absent in *cooperative robotics*.

Some definitions, such as *form finding* (h8098), with high "matching scores" did not spark much substantive commenting activity. However, other definitions, such as *cooperative robotics* (h8073), *collaborative robotics* (h8074) [40], and *fabrication-informed design* (h8075) [42] with high matching scores were moderately commented (three comments and two comments respectively) where the comments generally disagreed with the way the definition was expressed. Definitions for these terms do not appear in dictionaries and are still evolving in the literature and therefore are more prone to initiate such discussions.

One well-established term definition, *loads* (h8095), received a high matching score but comments requested modifications to add other types of loads and details that would make the definition less general. This specific term is interesting because the ASCE standards [23] provide a general definition of the term at the beginning of the standard, while chapter-specific definitions provide more precision on the type of loads expected in the particular structure being considered. The term *loads*, in general form, are "forces or other actions that result from the weight of all building materials, occupants and their possessions, environmental effects, differential movement, and restrained dimensional changes. Permanent loads are loads in which variations over time are rare or of small magnitude. All other loads are variable loads (see also nominal loads)" [23, pp. 1]. *Live loads*, for example, are "produced by the use and occupancy of the building or other structure that does not include construction or environmental loads, such as wind load, snow load, rain load, earthquake load, flood load, or dead load" [23, pp. 13]. It is possible to observe that the specific type of load—live load—expands on the occupants category that was first presented in the general *load* definition.

More recent terms such as *form finding*, nowadays present a similar substructure but still lack the exactitude of the definition for the term *loads*. Depending on the method used for form finding, the term can be specified as a numerical or physical method. The term *inverse design* [43, pp. 379], for example, was defined in YAMZ with structural engineering in mind, where the word *design* already carries the "embedded meaning" of solving an *inverse problem*, i.e., when one designs a structural member, they select the properties of the system based on constraints and with the intent of optimizing—however manually and crudely—for given loads and spans. The published definition of *inverse design* states that it is the natural sciences and engineering equivalent to the term *inverse problem*, which is used in a broader mathematical sense [43]. *Inverse design* has also been identified to be a term adopted by the form finding community [43] instead of the term *inverse problem*.

A comparison of the published definitions with the user-supplied definitions and examples provides some insight into how they connect to each other semantically. Looking at the term *form finding* which was common to all participants, we can compare keywords extracted using the YAKE! algorithm (scores are shown to evaluate relative rank within each set; YAKE! is sensitive to document length, which means that scores cannot be compared between different sets [44].) What we see in this limited sample is some overlap of specific words between the two sets of definitions which offers a baseline comparison between the two forms. Table 4 shows the top 10 terms extracted from user definitions and published definitions respectively. Terms which overlap between the two are highlighted with corresponding colors. YAKE! functions more effectively on unpreprocessed text which accounts for slight variations in the samples. In addition to *form finding*, three terms were set as keywords by the YAKE! algorithm in both sets (see highlighted terms in Table 4) *process*, *shape* and *structure*. The term *process* broadly categorizes *form finding* as a type of method, *shape* provides a synonym for the word *form*, and *structure* relates to the subject of discussion. The user definition keywords *optimal*, *maximizing*, and *loads* are not present

Table 4
Top ten keywords extracted from user and published definitions, and the corresponding YAKE! score.

User definitions		Published definitions	
Keyword	YAKE! score	Keyword	YAKE! score
optimal	0.127	shapes	0.264
finding	0.090	form-finding	0.257
process	0.078	process	0.224
Form	0.059	static	0.196
shape	0.047	structure	0.196
structure	0.044	controlled	0.193
maximizing	0.043	design	0.193
methods	0.040	equilibrium	0.193
loads	0.038	find	0.193
akin	0.038	forward	0.193

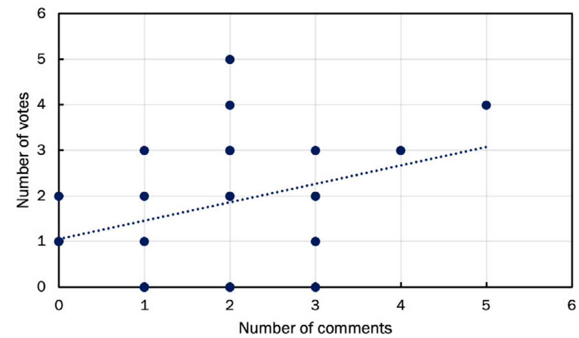

Fig. 4. Number of votes and comments for each definition entry in YAMZ.

in the top ten published definitions keywords, although they relate to the ideas of *design* (related to *load*) and reaching an *equilibrium* (related to *optimal*) state. Therefore, Table 4 shows some similarity between keywords extracted from published and user definitions, but a keyword such as *maximizing* indicate a more particular usage of the term by the users.

Parsing the data a step further shows how terms extracted from the individual user definitions aligned with each other as well as the published definition (see Table 5). These data varied greatly in terms of user engagement metrics such as voting and commenting. All of the various versions of *form finding*, with the exception of h8077, show overlap of individual words or phrases with the published definitions. The two versions which show the highest positive aggregate score, h8076 and h8098, show an important overlapping word *equilibrium* which was identified by the authors as a descriptor with high semantic relevance for describing the term. However, it does not seem to correlate with more commenting activity; h8076 had 5 comments but h8098 only 2.

These data showed that the two user-provided definitions with the matching word *equilibrium* were those with the highest upvotes. Other matching words did not provide any discernible correlation.

Comments accounted for the majority of the textual artifacts collected in the study and were analyzed in relation to other data to see if correlations arose. Comments were present for 23 terms and ranged from single instances (n = 6) to five comments (n = 1) with an average of two per term with comments. The comments are split close to evenly between initial responses to definitions (n = 23) and replies to other comments (n = 28). Most comments were substantive or less substantive which points to slightly greater user engagement with definitions, examples, and other prior comments. Terms *internal loading* (h8088), *form finding* (h8098), *inverse design* (h8099) were the only ones which received non-substantive comments which were not followed by substantive comments. Looking at comments with respect to voting (see Table 6), only one of the three highest voted terms had more than three comments. When we expand the subset to all terms with more than three votes (n = 9), there are still only three terms with more than two comments. One interesting aspect is that the most common term, *form finding* occupied more than half of all terms which received more than three votes. For terms which received fewer than two votes, three had no comments and the remaining nine ranged from one to three votes, averaging slightly less than two comments per term. While comments show some level of engagement, greater numbers of comments did not necessarily translate into increased votes as can be seen in Fig. 4.

4. Discussion

The research questions laid out in Section 1.4 provide a valuable framework for understanding the results. To recapitulate, the questions that were asked are: (1) How can professionals in the AEC disciplines, specifically in a subset of the academic form finding community, produce more consistent and insightful terminology? (2) How does a crowd-sourcing tool such as YAMZ assist in better terminology production, and how can we characterize user engagement?

To address the first question, we have engaged a group of researchers involved in architecture, engineering and construction in the form finding community at CE academic departments. This group demonstrated the use of the method implemented by the tool YAMZ to formalize technical terminology in a common online space. The method consisted of providing definitions, commenting and voting on others' definitions, and, lastly, editing initially provided definitions to incorporate comments. Using this method through the referred tool provoked situations where the users purposefully reflected on terminology. Building consistent and insightful terminology is exemplified by production of term differentiation which was previously used interchangeably: *collaborative robotics* and *cooperative robotics*. The entries specified that *collaborative robotics* (h8074) involves a human in the human–robot construction process and *cooperative robotics* (h8073) involves machine–machine interactions. Additionally, users built consensus on comments and votes surrounding the term *form finding*. Users diverged through comments and had a mixture of up- and down-votes in some instances of the defined term and ultimately agreed through comments and up-votes on particular entries of the term.

A subjective yet valid conclusion from these entries is that, by providing terminology differentiation and agreement or disagreement around definitions, the users produced more consistent and insightful terminology. It is beyond the scope of the present work to determine whether these specific examples will be impactful to the community at large. Future work with long-term analyses and broader user pool followed by surveys is required to produce any generalization to the broader field of CE. The few data points we present herein solely suggest that using a dedicated space for technical terminological definitions could foster preciseness in communication among academics and potentially professionals in the industry.

In many respects, the two questions are highly interrelated with the capabilities of YAMZ, as a collaborative space, to display the semantic effects of user engagement with terminology. The actions of defining, commenting, and voting made visible the various elements of constructing and refining terminology. The results obtained from the study offer several insights into the use of YAMZ as a specific instance of crowd-sourced methodology in a research group setting over a limited time span. Definitions and examples varied in length but averaged approximately 20 words after controlling for outliers on the high end (see Fig. 4). These features did not seem to affect the metrics of cross-user engagement such as voting or commenting. Similarly, commenting which occurred sequentially earlier in the study displayed a slight effect on voting; higher voted terms displayed more commenting activity than the lowest ranked terms, but the differences were not significant and could have been affected by a factor such as when the point in time when each term was initially entered. Half of the higher-voted

Table 5
Top ten word extraction and user engagement data for *form finding* definitions.

h8076		h8077		h8083		h8085		h8089		h8094		h8098	
Term	YAKE!	Term	YAKE!	Term	YAKE!	Term	YAKE!	Term	YAKE!	Term	YAKE!	Term	YAKE!
Applied	0.158	Analytical	0.386	Finding	0.158	Akin	0.42	Designing	0.184	Defined	0.158	Design	0.086
Boundary	0.158	Deformation	0.386	Finds	0.158	Darwinism	0.42	Finding	0.184	Efficient	0.158	Encapsulates	0.086
Conditions	0.158	Maximizing	0.386	Geometry	0.158	Idea	0.42	Fulfills	0.184	Employment	0.158	Equilibrium	0.086
Equilibrium	0.158	Methods	0.386	Optimal	0.158	Minimizes	0.42	Process	0.184	Finding	0.158	Family	0.086
Loads	0.158	Minimize	0.386	Optimization	0.158	Optimal	0.42	Specific	0.184	Loads	0.158	Finding	0.086
Objective	0.158	Numerical	0.386	Prespecified	0.158	Resulting	0.42	Form	0.133	Optimal	0.158	Generate	0.086
Set	0.158	Efficiency	0.316	Process	0.158	Forms	0.399	Properties	0.112	Process	0.158	Load	0.086
State	0.158	Stresses	0.316	Properties	0.158	Potential	0.335			Shape	0.158	Methods	0.086
Structure	0.158	Constraints	0.171	Satisfies	0.158	Creating	0.173			Size	0.158	Set	0.086
Calculating	0.096	Determining	0.153	Shape	0.158	Implicitly	0.173			Structure	0.158	Shape	0.086
Engagement metrics		Engagement metrics		Engagement metrics		Engagement metrics		Engagement metrics		Engagement metrics		Engagement metrics	
Comments	5	Comments	2	Comments	3	Comments	1	Comments	4	Comments	3	Comments	2
Magnitude vote	4	Magnitude vote	4	Magnitude vote	2	Magnitude vote	0	Magnitude vote	3	Magnitude vote	3	Magnitude vote	3
Up/Downvotes	3/1	Up/Downvotes	1/3	Up/Downvotes	0/2	Up/Downvotes	0/0	Up/Downvotes	1/2	Up/Downvotes	0/3	Up/Downvotes	3/0
Aggregate vote	2	Aggregate vote	−2	Aggregate vote	−2	Aggregate vote	0	Aggregate vote	−1	Aggregate vote	−3	Aggregate vote	3

Table 6
Terms defined in YAMZ with the corresponding number of votes and comments. ARKs provide a unique identifier to distinguish different entries for the same term (see Section 2.4.).

Highest voted terms				Lowest voted terms			
ARK	Term	Votes	Comments	ARK	Term	Votes	Comments
h8075	Fabrication-informed design	3	2	h8079	Structural detailing	0	1
h8089	Form finding	3	4	h8081	Tectonics in architecture	0	1
h8090	Self-supporting structure	3	2	h8084	Shape optimization	0	3
h8093	Structural health monitoring	3	1	h8085	Form finding	0	1
h8094	Form finding	3	3	h8095	Loads	0	2
h8098	Form finding	3	2	h8096	Structural detailing	0	2
h8076	Form finding	4	5	h8074	Collaborative robotics	1	3
h8077	Form finding	4	2	h8080	Fabrication-informed design	1	0
h8078	Boundary conditions	5	2	h8088	Internal loading	1	1
				h8091	Structural detailing	1	0
				h8092	Fabrication-informed design	1	3
				h8097	Inverse design	1	0

terms have lower sequential ARK numbering which might indicate that earlier entry could allow users in the study more time to evaluate terms. However, an inverse pattern does not seem to occur among the terms with the lowest voting activity where the ARK sequences show greater variations in numbering which includes terms entered at all points in the experiment. In this group, users engaged with a range of definitions through comments, but that engagement did not necessarily translate into voting activity. The fact that the terms received no votes points toward the need for further study to understand what drives user engagement.

The comparison of data regarding term extractions from definitions for *form finding* (see Table 5) yielded promising avenues for further study. Definitions showed varying degrees of overlap in verbiage both among themselves and with external, published definitions. Many of these collocations are less relevant, such as repetitions of the words and phrase *form*, *finding*, and *form finding*. The majority of the *form finding* definitions displayed negative voting or no votes at all. The two positively voted terms contained the word *equilibrium*, which suggests that the word has additional importance in how users evaluate the term. Functionally for CE, a "form" is deemed "found" when it is in static equilibrium, and therefore, mentioning this term probably made these definitions more complete, regardless of other specifications made in the definition text. This combination of voting and keyword extraction could assist in locating relevant features across definitions. By contrast, locating features of downvoted terms could show aspects of definitions which could improve precision. The limitations of this analysis are several. First, the extracted keywords were limited to the top ten (h8089 was short and contained fewer than ten extractable words); an expanded list could show greater variance. The size of the subject pool also limits the perspectives which could alter voting and commenting. Comments ranged in length and substantiveness across the sample, but these displayed no discernible pattern of effects among comment conversations or on voting.

The instance where the natural sciences and engineering use the term *inverse design* rather than the broader mathematical term *inverse problem* highlights how different disciplines develop the same idea but use slightly different terms. These examples highlight the importance of having a tool such as YAMZ that allows clusters to reach their own consensus on the specificity of the term, as well as the ability to search and learn how other clusters use the same term. Additionally, the example where *cooperative robotics* (h8073) and *collaborative robotics* (h8074) generate similar definitions and user engagement highlights the need to provide a method of term correlation within the tool—a feature not currently available.

These positive aspects are tempered by the limitations present in the study. The sample of participants and terms chosen represent a small, academic subsection of CE. Both the user pool and term selection are not necessarily representative of the CE field as a whole or the vocabulary they use. The set of terms employed is generally emergent, and this study examines how definitions can be compared and degrees of consensus can be found among members regarding such terms. These limitations further point toward the need to conduct a larger more representative study with the methodology implemented in YAMZ to understand how terminology is defined and refined through mechanisms such as commenting and voting.

4.1. Semantic implications

Crowd-sourced definition efforts produce a variety of perspectives which allows for disparate viewpoints to arise. In a system such as YAMZ, definitions allow individuals to emphasize aspects of terminology which are of greater relevance to individual goals. This emphasis on specific communal aspects of definitions is most on display in the sample in the various definitions of *form finding* which all stem from a shared concept of the term but rely upon individualized understanding of the term in everyday usage, e.g., asking a person to define a term will rarely yield a dictionary definition. While intracommunal usages might find low variation in how terms are used, such as that in this study, intercommunal use might show greater degrees of difference or ambiguity in usage. Dictionaries often include gradations of definitions to account for different usages. Furthermore, these variations allow for areas of convergence and divergence to emerge from groups of terms. When combined with voting, communities decide the definitions considered most salient to their field. Voting in YAMZ functions as a possible method of validating a definition, but it is still subject to some of the stresses which occasion formal methods of terminological production, such as a small bloc of dedicated users exerting outsize influence based on greater engagement or motivation. However, a definition that is not highly voted has other forms of value. In both cases, the bottom-up structure of the method implemented in YAMZ which strives for greater user engagement allows for the possibility to reveal underlying biases through greater representation of stakeholders. However, there is always the possibility that a non-diverse user pool could reinscribe prior cultural or disciplinary biases. PIDs allow individuals to utilize terms which might better suit individual needs, though not highly voted. Due to the limited size of this study, it is difficult to examine broader voting and usage patterns which may give a clearer picture of term deployment both within and without YAMZ. These considerations present opportunities to address deficiencies in the practical production of civil engineering terminology, such as standards, by allowing greater participation of interested stakeholders.

Individual usage does allow for greater term disambiguation. Users can compare definitions and examples from similar or competing versions of terms. Users can link to preferred usages, offering control over specific aspects of how they want to employ a term. Because users develop and maintain their definitions, it offers a sense of ownership regarding vocabulary and engages users to discuss the relative strengths and weaknesses of each others' definitions and examples through forums such as commenting. This investment in terminology can possibly contribute to higher quality, more precise metadata based on researcher's specific use of terminology as supplied by the PID. These efforts aiding term disambiguation can have important impacts for Findable Accessible Interoperable Reusable (FAIR) data initiatives [45] assisting interoperability of data across disciplines by clarifying specific terminology used to describe data. This support is further aided by the use of ARKs to provide continuity of data across a variety of information environments; however, PIDs require maintenance by their host institutions which could affect their long-term stability in the event of closure, loss of funding, or other unforeseen event.

4.2. Broader applications

The use of the crowd-sourcing methodology could range from individual use in the academic writing environment to larger groups during the technical committee meetings. The individual use of YAMZ may serve the purpose of citing a specific use of technical terminology in scientific writing. A definition provided in the tool can be cited using ARKs in research publications. The reader can be directed to the definition and learn from the history of comments how that definition came to be. ARKs provide a standard reference point both within and without YAMZ. Within the application, they serve as a database key, a unique identifier that disambiguates homonymic terms. Outside the application, ARKs allow users to leverage terminology for individualized ends, such as linking specific vocabulary terms to denote idiosyncratic usage. This external use allows users to clarify or highlight personal differences over and against more conventional usage of a term. As can be seen in this demonstration, each user defined *form finding* differently and all definitions diverged from the published definition. Each of these aspects relates directly to the authors' second research question regarding the ability of YAMZ to assist terminology production and characterize the various forms of user engagement.

Across a variety of knowledge areas and settings, YAMZ could assist in vocabulary development and disambiguation. The three categories of formal terminological consensus building spaces introduced in Section 1.2 identify areas where YAMZ could provide the most impact.

First, in small groups such as the one in the present exploratory analysis may leverage the tool as a way to build consensus on how to use terminology in the research group. The terminology can later be used by new members of the group and other collaborators, as well as cite the YAMZ entries in publications. Terms such as *cooperative* and *collaborative robotics* that are still evolving [46,47] now have unique identifiers and definitions to differentiate and track the term evolution as new definitions might be entered into YAMZ.

The second category includes larger groups who might also use this tool at the beginning of the technical report-making process where researchers and industry leaders come together—usually in conferences or conventions—to workshop ideas and define the scope of the technical report. In these workshops, the group has an opportunity to find terminology in need of discussion and set up the space for initial discussions in the YAMZ platform. The group would then be able to create a unique tag for the team as demonstrated at a smaller scale in the present work, to publish definitions and comments during the following months of discussion to reach a consensus. The commenting and voting processes offer the opportunity to streamline participant input regarding terms under consideration. This can be further facilitated by the fact that YAMZ can be implemented as a standalone instance through the publicly available repository [48] which can be customized by users for specific needs. Furthermore, YAMZ can be used in the AEC industry, where specific vocabulary and procedures take years to develop within and between companies [7]. Companies have identified the diverging vocabulary between architecture and civil engineering fields and have built routines to bring new members into the loop [7].

The third category could similarly benefit from a tool such as YAMZ to track the terminological nuances of the AEC disciplines and provide references to field-specific definitions. The feature of maintaining distinguishable entries of the same term can provide a means of disambiguation in digital workflows.

5. Conclusion

The data collected in this exploratory analysis shows that a crowd-sourcing tool like YAMZ can effectively collect data from community members as the exploratory analysis shows in this CE study. We showed that YAMZ has potential to be used as a discussion tool to track and formalize the process of initial discussions on new and nuanced terminology. The possibility to include many entries for the same term and to retain each discussion from those different entries shifts the terminological ownership to users and research or industry groups. For example, the users of this study provided specifics in the use of terms such as *form finding* relating to their field.

Broadening the user group will enable further statistical discovery of how users interact and comment and change their initial definitions in extended use of the tool. Further studies exploring a broader set of terms within the AEC community involving a broad set of stakeholders would allow us to develop a clearer understanding of the connections between commenting, voting, definitions, and examples. Each of these aspects may reduce semantic ambiguity among stakeholders in AEC projects. Ultimately, the present study demonstrated how YAMZ can be employed in research groups to build terminological consensus and to inform research, particularly in the case of cooperative and collaborative robotics as discussed in Section 4, showed how YAMZ may assist in better production of terminology, especially by providing a crowd-sourced environment to formalize rapidly evolving terminology, presented the functions of individual features, and presented possible scenarios for applications of this tool, or the method here employed regardless of tool implementation, in the AEC community to produce more insightful vocabulary.

CRediT authorship contribution statement

Isabel M. de Oliveira: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Scott McClellan:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Christopher Rauch:** Software, Data curation. **Sigrid Adriaenssens:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Jane Greenberg:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix. List of terms

The published definitions of the terms used in the present work are listed in this appendix. Definitions are enumerated when more than one source is used.

Form finding. (1) "Form finding is a forward process in which parameters are explicitly/directly controlled to find an 'optimal' geometry of a structure which is in static equilibrium with a design loading." [49, pp. 2] (2) "The geometry is an unknown; form finding is the generation of geometry." [49, p. 2] (3) "'form-finding', i.e. finding the basic static shape of the structure (under pre-tension forces only)," [50, pp. 15] (4) "In general, the process of form-finding should yield optimal structural shapes: shapes that would satisfy the functional requirements and attendant durability and strength at a minimum cost." [50, pp. 23]

Shape optimization. "Shape optimization has variables acting on the geometry of the structure, without modifying the topology. Practically, in discrete structures, the node coordinates are often used directly as parameters to modify the geometry, but more advanced parameterizations are available (see Section 5.4 and Appendix D)." [49, pp. 4]

Inverse design. "Inverse design, also known by the term 'inverse problem', is a collection of relatively new research approaches that are growing in popularity in natural sciences and engineering. In general terms, in the case of an inverse design problem, the particular configuration of a material, geometry or process is determined as the result of a targeted search activity (Fig. 15.1). While the techniques adopted to perform such a search can differ, what makes the idea of the inverse approach unique is that it formulates the functional requirements for a given design as an optimization problem. This means that in an inverse approach, a parameter search is systematically carried out, in an automated way, until a design solution is found that meets the specified objectives in the best way possible." [43, pp. 379]

Boundary conditions. "Boundary (and Continuity) Conditions. When solving Eqs. 12-8, 12-9, or 12-10, the constants of integration are determined by evaluating the functions for shear, moment, slope, or displacement at a particular point on the beam where the value of the function is known. These values are called boundary conditions. Several possible boundary conditions that are often used to solve beam (or shaft) deflection problems are listed in Table 12-1. For example, if the beam is supported by a roller or pin (1, 2, 3, 4), then it is required that the displacement be zero at these points. Furthermore, if these supports are located at the ends of the beam (1, 2), the internal moment in the beam must also be zero. At the fixed support (5), the slope and displacement are both zero, whereas the free-ended beam (6) has both zero moment and zero shear. Lastly, if two segments of a beam are connected by an "internal" pin or hinge (7), the moment must be zero at this connection.(...)" [51, pp. 578]

Loads. (1) "LOADS: Forces or other actions that result from the weight of all building materials, occupants and their possessions, environmental effects, differential movement, and restrained dimensional changes. Permanent loads are loads in which variations over time are rare or of small magnitude. All other loads are variable loads (see also nominal loads)." "NOMINAL LOADS: The magnitudes of the loads specified in this standard for dead, live, soil, wind, tornado, snow, rain, flood, and earthquake loads." [23, pp. 1] (2) "Load†. Force or other action that results from the weight of building materials, occupants and their possessions, environmental effects, differential movement, or restrained dimensional changes." [25, pp. lvii] According to AISC, "terms designated with † are common AISI-AISC terms that are coordinated between the two standards development organizations." [25]

Self-supporting structure. (1) "A self-supporting surface can support its self-weight by a purely compressive stress field. A structure of this class does not exhibit bending when design loading (typically the surface structure's self- weight plus any other dead loads) is acting on it; therefore, employing self-supporting surfaces is advantageous for construction of compressive structures, such as masonry and reinforced concrete shells." [52, pp. 1] (2) "Of a physical object or structure: not requiring support in order to maintain its form or position" [53] (3) "Here "self-supporting" means that the structure, considered as an arrangement of blocks (bricks, stones), holds together by itself, with additional support present only during construction." [54, pp. 871]

Structural design. "The process of establishing the physical and other properties of a structure for the purpose of achieving the desired strength, serviceability, durability, constructability, economy, and other desired characteristics. Design for strength, as used in this Specification, includes analysis to determine required strength and proportioning to have adequate available strength." [25, pp. liii]

Structural detailing. (1) "Section design and detailing entails determining what size section or quantity of reinforcement is required to carry the load. The programs will often be dedicated to particular structural element types and materials, such as steel beams or concrete foundations, or to structural arrangements such as trusses or portal frames. They will typically derive the forces and moments from applied loads, though some will have an application programming interface to allow other programs or scripts to make use of them." [55, pp. 40] (2) "Detailed design is essentially a mechanical process with few options; as long as you know the inputs then you can calculate the output. As such, it is a common task for both graduates and computer programs, as well as a skill needed to pass your university exams." [55, pp. 8]

Internal forces. In mechanics of materials, statics is primarily used to determine the resultant loadings that act within a body. For example, consider the body shown in Figs. 1–2a, which is held in equilibrium by the four external forces. In order to obtain the internal loadings acting on a specific region within the body, it is necessary to pass an imaginary section or "cut" through the region where the internal loadings are to be determined. The two parts of the body are then separated, and a free-body diagram of one of the parts is drawn, Figs. 1–2b. Notice that there is actually a distribution of internal force acting on the "exposed" area of the section. These forces represent the effects of the material of the top part of the body acting on the adjacent material of the bottom part. Although the exact distribution of this internal loading may be unknown, we can use the equations of equilibrium to relate the external forces on the bottom part of the body to the distribution's resultant force and moment, F and Mr. at any specific point O on the sectioned area, Figs. 1–2c. It will be shown in later portions of the text that point O is most often chosen at the centroid of the sectioned area, and so we will always choose this location for O, unless otherwise stated. Also, if a member is long and slender, as in the case of a rod or beam, the section to be considered is generally taken perpendicular to the longitudinal axis of the member. This section is referred to as the cross section." [51, pp. 7]

Cooperative and collaborative robotics. (1) "Machines have the ability to manipulate material cooperatively, enabling them to materialise structures that could not otherwise be realised individually." [41, pp. 24]

Under a section named "Cooperative Robotics" the following definition was provided. (2) "Nowadays, HRI is available and safe with the popularization of Collaborative Robots, generally known as Cobots, which enable safe interaction between humans and robots during the execution of the tasks." [40, pp. 95446]

Fabrication-informed design. Fabrication-*informed* design is used interchangeably with fabrication-*aware* design. "Fabrication-aware design focuses on developing geometric design algorithms that facilitate fabrication." [42, pp. 164]

Tectonics in architecture. "Tectonics in architecture is defined as "the science or art of construction, both in relation to use and artistic design." It refers not just to the "activity of making the materially requisite construction that answers certain needs, but rather to the activity that raises this construction to an art form." It is concerned with the modeling of material to bring the material into presence: from the physical into the meta-physical world" [5].

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