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Evaluating Wikis as a Communicative Medium for Collaboration Within Colocated and Distributed Engineering Design Teams

Wikis, freely editable collections of web pages, exhibit potential for a flexible documentation and communication tool for collaborative design tasks as well as support for team design thinking early in the design process. The purpose of this work is to analyze dimensions of wiki technologies from a communication perspective as applicable to design. A wiki was introduced in a globally distributed product development course, and the experiences and performance of colocated and distributed teams in the course were assessed through observations, surveys, and site usage analytics. With a focus on communication in design, we explore the advantages and disadvantages of using wikis in student engineering design teams. Our goal is to use wiki technologies to enhance support for design processes while exploiting the potential for increasing shared understanding among teams. Distributed teams used the wiki more as a design tool and were more supportive of its use in the course whereas colocated teams used it for documentation. The usage patterns, the number and type of files uploaded, and the wiki structure provided indicators of better performing teams. The findings also suggest ways to improve and inform students about best practices using the wiki for design and to transform the wiki as a support tool for communication during early design collaboration.
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1 Introduction

Design is increasingly recognized as a social process [1,2] requiring rich and effective communication and collaboration among participants. With advancing complexity of industrial and consumer products amidst continuing globalization, new opportunities for distributed teamwork and international collaboration have also expanded. Along with these new opportunities, however, arise new challenges. One such challenge is to understand and enhance design communication among distributed collaborative teams. While face-to-face communication has often been recognized as the easiest method for communication of problems and decision-making [3], it is often not feasible for team members (especially those of larger groups) to maintain face-to-face contact throughout the design process. Furthermore, communication processes, problem solving activities, and directions are relatively unstructured in early design stages. This paper proposes the use of wiki as a communication and documentation tool for distributed design teams and describes several methods for evaluating the effectiveness of this tool for enhancing shared understanding in design. As several advanced collaboration tools exist for later stages of the design process, this paper will focus on the use of wiki for collaboration during early design. In contrast to prior work, we critically examine the role of a wiki to support early design through a communication framework. Specifically, we compare colocated and distributed teams while analyzing patterns of the wiki usage. User survey of the use of the wiki highlights both the drawbacks as well as utility of the wiki in early design. An overview of wikis along with their potential uses for engineering design is presented in Sec. 2; Sec. 3 identifies several key questions for joining the work of communication and engineering design and presents directions for future work. Concluding remarks are provided in Sec. 4.

1.1 Tools for Early Stage Design Support. One view of the design process is as an iterative map from the customer requirements to the final design of the product [4]. Design problems are usually ill-structured, possess incomplete or ambiguous specification of goals, have no predetermined solution path, and require integration of knowledge from multiple domains. The design process is commonly considered to consist of four distinct phases: task clarification, conceptual design, embodiment design, and detailed design [5]. We consider early design to encompass the task clarification and conceptual design phases. Early design generally includes activities such as defining the problem, generating concepts, selecting among these concepts, and making decisions. During early design, qualitative customer requirements are mapped to functional specifications and then several alternatives are developed, which achieve those functions. Later stages of design (i.e., embodiment and detailed design) focus on refining the concepts and generating the form of the product in sufficient detail for subsequent manufacture and design validation.

A large body of literature exists on developing models, methods, frameworks, and tools for supporting designers in the development of engineering products. These tools allow designers to understand, decide, synthesize, and communicate design-related information and fall under three broad categories [6]: (1) store, search, modify, and share (designed artifacts and knowledge about design), (2) express and edit (design representations), and (3) interact to uncover, explore, and understand meanings.

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Several "specialized" tools such as computer aided engineering systems exist primarily for representing, modeling, and analyzing designs [7]. Since both information and activities become more structured as design progresses, very few specialized tools are applicable to early design compared to later stages [8,9]. Designers, nevertheless, make use of existing general-purpose tools to perform design activities (see Fig. 1). General-purpose tools by definition are not restricted to design and, therefore, provide the flexibility needed to represent, document, and communicate unstructured information that is encountered in early design (Fig. 2).

Due to the depth and breadth of knowledge required to develop a complex product in modern society, it is no longer feasible for an individual to work alone on a compound multidisciplinary and multiskill design project. This introduces a growing need for both effective communication practices and innovative knowledge management (KM) tools [10]. Because of its nature of speed and flexibility, wikis may provide a unique utility to early design, including inherent properties that better facilitate the rapid emergence, modification, and exchange of ideas during early design. These systems are easy to use with little or no learning required and freely available. We hypothesize that due to the flexible structure of the wiki systems, wikis will be more useful during earlier phases of design, when the tasks involved and types of information are less structured. However, even though this phase accounts for a significant portion of the cost committed in design [11], there are no ways of measuring the effectiveness of general-purpose tools in early design phases.

The aim of this paper is to provide a framework for evaluating wikis as an early design tool from a communication perspective. Our aim raises the questions:

1. Are wiki tools useful in design processes? How can the "utility" or "effectiveness" of wiki tools be measured?
2. How is communication within a design team influenced by the use of wiki technologies?
3. How does the use of the wiki differ for colocated versus distributed teams?
4. How can wiki tools be used to support critical activities in design?
5. How do wiki tools and environments enhance (or decrease) shared understanding among teams?

1.2 Communication Aspects. A communication approach to engineering design focuses on the processes and structures of communication during design collaborations, as well as its texts (the spoken and written representations). Key to understanding design communication is an examination of knowledge generation and shared understanding in design processes. The production and sharing of knowledge in engineering design includes both explicit and tacit knowledge [12]. Nonaka [12] defines explicit knowledge as knowledge that can be codified and communicated symbolically, such as through written documentation and graphs. In contrast, tacit knowledge represents knowledge gained through experience, in specific contexts, that includes both cognitive and technical elements. Furthermore, knowledge is socially embedded [13] and constructed through processes of shared deliberation, collaboration, and communication. While decision and group support technologies and systems have been successful in providing support for the production of explicit knowledge, tacit knowledge—which is particularly salient during early design and innovation communication processes—has been more difficult to support.

Research examining whether computer-based technologies constrain or enable the communicative processes of innovation continue to yield mixed results, likely a result of the variances and complexities in types of media and technology employed. Results from previous research indicate that computer-supported groups can outperform, under perform, or show no difference in the quality of ideas generated [14]. Furthermore, because distributed groups and teams have fewer opportunities for face-to-face communication, the collaboration and development of innovation, creativity, and knowledge production during early design may be more difficult. For example, in the process of innovative "brainstorming" [14], communication is frequently fluid, is unformed, and emerges directly from group interaction—that is, it is both socially embedded and socially produced. Ideas flow quickly, and knowledge emerges in forms that are not always represented through fixed representations. Therefore, that which is documented as explicit knowledge is typically a reduced form of the interactive process and also affected by the influence, power, and representation of particular individuals in the group.

The structuring of communication and organizing processes during engineering design changes with time, with early design phases benefiting from greater flexibility, and later design phases benefiting from the more highly structured and formalized technologies typically found in engineering design industries. Adaptive structuration theory [15,16] provides a framework for examining the processes that structure group interaction and the subsequent emergence of technological systems from such processes, along with the appropriations of interaction that provide concretizations of design collaborations.

Because of the complexities inherent in knowledge management, tools and technologies to support KM systems and technologies have been inadequate or restrictive in allowing sufficient discussion and representation of early design communication. For example, Flanagin notes "the ability of new technologies to support KM in a meaningful manner depends on the types of knowledge they are designed to capture and share, the features and design of the technologies themselves, and the social dynamics among organizational members" [17]. Most technologies have been identified and developed to capture, store, and disseminate

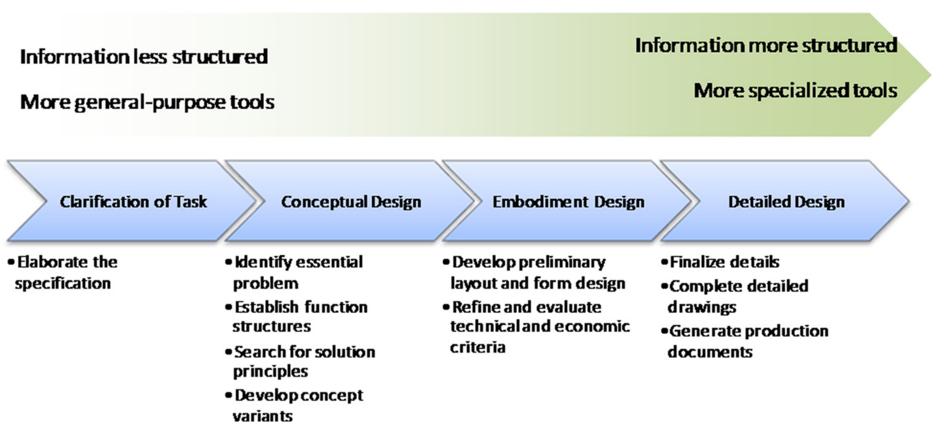

Fig. 1 The early design phase involves more general-purpose tools than later phases

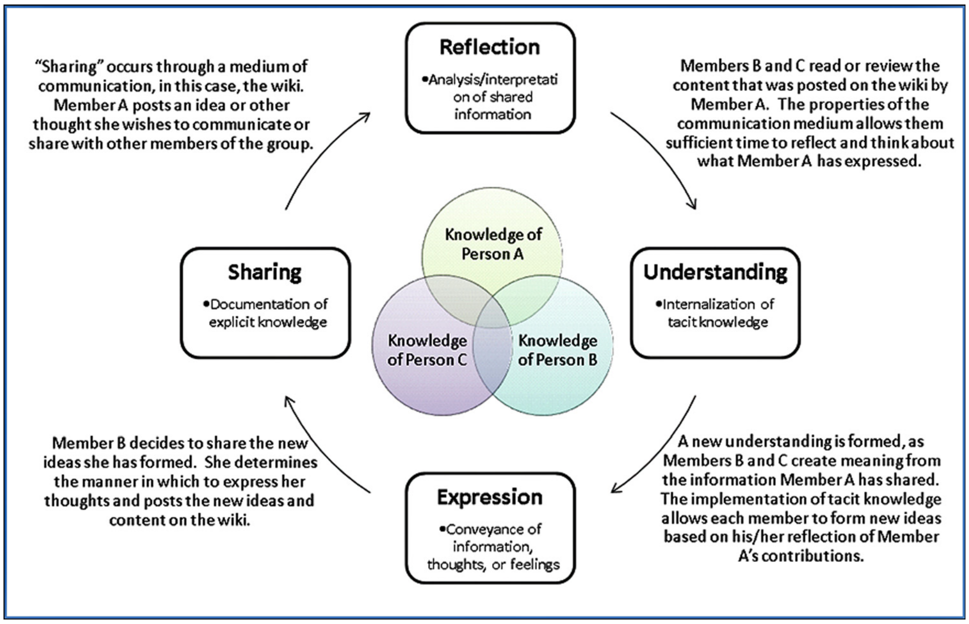

Fig. 2 Role of communication in shared understanding among teams using wiki

explicit knowledge of individuals, neglecting the important elements of tacit knowledge as well as the social process by which innovations emerge and are developed.

Flanagin highlights three issues of older KM technologies: (1) the tendency to artificially reduce knowledge complexity [18]; (2) the focus on the individual as the primary source of knowledge; and (3) the failure to recognize the possibility that knowledge may be located within a network of interactions through both shared and unshared understandings [19]. Wiki technologies provide the possibility of creating a richer environment [20] and the capability to support representations of early tacit knowledge, as well as the textual, visual, and other representations of design communication to better represent and document this phase of engineering design. To the best of our knowledge, early design communication using the wiki as a platform has not been examined using a communication framework.

1.3 Design Aspects. Three main aspects of design that are closely related to the communication elements will be analyzed. The first aspect pertains to the different types of information used in design and the manner in which wikis are employed for documenting and communicating information. The information communicated and documented in engineering design includes sketches, design requirements, constraints, functions, behaviors, concepts, and ideas. Visual representations are especially important in design for sharing/conveying ideas and for documentation. While wikis are currently used primarily to document textual information, images can also be loaded and arranged on the web pages. Because pen and paper is a primary medium used in early design, the inability to easily record sketches and other hand-produced visual representations is one weakness in their present state for use in early design.

The next aspect pertains to the stages of design during which the wiki is useful. While the focus of this paper is on early design stages, the ideas presented can be extended to other phases of design as well. During early design, the problems are ill-defined and the processes are relatively unstructured. Ideas are communicated frequently as the team revises the problem scope and redefines the objectives and requirements. Iteration is a critical component throughout the design process, but the early stages of design especially require frequent alterations.

In discussing problem-solving, Jonassen explains that the cognitive operations involved have two critical attributes: the "mental representation of the situation in the world" and "some activity-based manipulation of the problem space" [21]. It is through these cognitive activities, as well as communicative and interactive activities, that design problems become more fully understood by the participants. As understanding of the problem continues to develop through iterations of the "activity-based manipulations," more design-specific tasks evolve, gradually transforming the problem space into a solution space. In a collaborative environment, each of these tasks involves communication and generation of a "shared vision" to build upon existing notions of the problem and advance the design to accepted solutions.

The notion of design as a problem solving process is widely supported in literature. Design problems are not fully specified and, therefore, require "drawing upon our knowledge to compensate for missing information and using this knowledge to construct the problem space" [22]. During this complex problem solving process, several phases are generally enacted: preliminary design, refinements, and detail design. Goel and Pirolli note that design team members frequently "return to an earlier phase as previously unnoticed aspects emerged" [22], suggesting that design phases are both iterative and overlapping. In addition, the time spent in different design phases varies as a result of the variations in how the design process is conducted. Thus, design is unique for each problem and for each team, and there are diverse factors that influence the thoughts and communication among team members.

Throughout the early stages of the problem-solving process, the communication processes, activities, and ideas generated are relatively unstructured. It is this unstructured aspect of early design and the communication processes that occur that provide strong potential for the wiki to be an effective tool. Early design communication mediums require the ability to continually evolve to support more efficient means of communication.

1.4 Communication in Design Teams. Designing is a problem solving process that demands creativity and innovation. It requires attention, imagination, and communication in order to manifest a world not yet seen [23]. Through this process of problem solving, designers interact with others to gather information, generate ideas, and communicate their thoughts. The result is generally a product: a device, a program, or a process. Because of the significant involvement of multiple people during the design and in the presentation of the outcome, design is considered a social process [1], one that is "rarely a solitary activity … [but rather] …

is a social interactive process" [24]. While individuals may conduct certain elements of a design, the process (within both academic and industry settings) most often occurs among a collaborative group of individuals. This team consists not only of designers but may also include engineers, technicians, managers, manufacturing personnel, and others. Because design is collaborative, the interactions among the team members and the understanding that each member possesses about the design/project goals, their individual roles, the roles of others, and the expected outcomes, are critical aspects of design.

The process of collaboration includes the communication and the sharing of information [25]. It is through this collaborative and communicative process that design ideas are discussed, shared, and transformed into various communicative products, including visual representations, and eventually implemented or manufactured. Because teamwork is such a central part of current design practices, many researchers and practitioners highlight that "communication is one of the critical success factors of collaborative design" [26]. It is crucial, therefore, to recognize the role that individuals play in the design process, both individually and as teams.

Many researchers have studied the social processes of design [27,28] as well as the communication aspects of design teamwork. From a fundamental and functional standpoint, communication is defined as "the cognitive and social process by which messages are transmitted and meaning is generated … [and] the vehicle by which behavior is coordinated" [26]. In addition, research recognizes that communication influences human behavior, and as such, communication among design teams influences behaviors as well as the outcomes of the design process. Hill et al. note that "communication in a social setting is often characterized as the creation of shared understanding through interaction" and that developing shared understanding is a key factor in high performing teams [29]. Furthermore, productive teams constantly build upon their common knowledge and shared understanding of the problem or situation. The notion of "shared cognition" was first introduced by Cannon-Bowers and Salas to understand team and organizational performance [30], and they posited four main categories of shared cognition: task-specific knowledge, task-related knowledge, knowledge of teammates, and attitudes/beliefs [30]. While each contributes to team effectiveness in studying design teams, task-specific knowledge and task-related knowledge are of primary interest. Assessing shared cognition contributes to understanding team performance by examining how members of effective teams interact with one another. Cannon-Bowers and Salas suggest that "in effective teams, members have similar or compatible knowledge and that they use this knowledge to guide their (coordinated) behavior" [30]. By examining how design teams develop shared understanding through interaction with other team members, researchers can develop and improve communication tools specific to engineering design.

While communication is a critical aspect of engineering design, there are few tools that provide sufficient means for communicating, sharing, and recording ideas during early design, especially among distributed teams. Existing tools have several disadvantages when used for design, depending on the associated activity and the medium of communication implemented. Sketching on paper, for instance, is often used in early design stages to convey ideas among team members. Visual representations can express conceptual ideas in ways that more clearly convey the thoughts of the originator than textual representations. Among distributed teams, however, it is difficult to share sketches and visual representations during the idea generation process. Finally, it is important to consider the participants in the design process who act as agents for communication. Ullman provides an extensive list of design team members, which includes product design engineer, product manager, manufacturing engineer, designer, technician, materials specialist, quality control/quality assurance specialist, analyst, industrial designer, assembly manager, and vendor's or supplier's representatives [11]. The various members participating in the design process are important because each brings a unique background and knowledge to the design team. Their individual training in different fields combined with their joint experiences provides a critical foundation for working together as a team. Each team member will develop an understanding of their own roles in the team along with the roles of the other members, generating shared cognition and mental models through this communicative and interactive process.

When explaining the notion of shared mental models, Cannon-Bowers et al. note that "shared situation or shared problem models include common understanding of the problem, goals, information cues, strategies, and member roles, all of which are grounded in the team's more general models of the task and team. They provide a context in which communication can be interpreted, and a basis for predicting the behavior and needs of other members" [31]. In design teams, especially globally distributed groups, which often involve many members each with different roles, it is essential that members know whom to communicate with and when to be productive in achieving a common goal. The use of a wiki in design is a means for providing a central point for asynchronous communication between large or small design teams.

2 Wiki and Design

While several mediums exist for communication within design processes, wiki appears to be unique in that it "more closely emulates a real verbal discussion [as compared with e-mail or shared folder/file access], with the added feature of being persistent" [32]. Wikis and semantic wikis are based upon Web 2.0 [33] and semantic web technologies. These technologies can enhance distant collaborative interaction and support the documentation and exchange of explicit knowledge, through an easy to use tool and environment.

A wiki is a database of interactive web pages that allows members of a user group to collectively edit the same material from nearly any computer with an internet connection [32]. The main purpose of a wiki is to provide an easily accessible platform for recording and sharing information in a single location. With this interactive exchange, "members can collaborate on content, either in real time or asynchronously, by editing the same document (or documents)" [32]. Wikis, along with other interactive Web 2.0 technologies, are dramatically changing the way the internet is used. While the internet and the World Wide Web was dominated early by noninteractive technologies, coded and constructed by programmers and web designers using specialized languages, Web 2.0 technologies, such as wikis, weblogs, and social networking sites, are highly social and interactive [34]. To further explain the notion of two-way communication via the internet, a more detailed description of wikis is provided in Sec. 2.1, along with an explanation of the current uses of wiki both apart from and within engineering design.

Two advantages of using wiki in engineering design lie in the potential for enhanced communication and improved documentation. The university setting is an excellent platform for implementing and studying the use of wiki in design, as most students are experienced using computers and the internet, and often use computers as their primary source of documentation. In addition, using wikis for engineering design communication and documentation can lead to improved team efficiency, better records for design reuse, an exploration of other design wiki spaces for ideas and knowledge sharing, and the support of reflective learning [35].

2.1 Overview of Wiki. The wide accessibility of wikis [32] has enabled its use in a wide range of applications including online encyclopedia, Wikipedia [36], organizational and communication purposes, and as collaboration tools in software engineering projects. Wikis are software systems that allow users to easily generate, publish, and edit web pages, i.e., open content management systems; they are one way of enabling computer-supported cooperative work [32,37]. The first wiki, implemented by Ward

Cunningham to allow easy exchange of information in a software development project, was designed with the intention to create "the simplest online database that could possibly work" [32]. Today, user-friendliness is still a central goal of wiki development. Wikis are dynamic in that they allow users to edit existing pages or create new pages linked from existing pages. Two main elements of a wiki are the wiki pages and the wiki engine. The wiki pages are created and edited by users and contain the actual content and information, which is displayed. The wiki engine is the software system, which provides the functionalities for viewing, editing, and publishing the wiki pages on the internet. Wikis have become increasingly popular in recent years and provide a platform for electronic collaboration that supports documentation editing and archival and flexible layout structures, in a user-friendly web-based platform, that is, both customizable and ubiquitously accessible.

A wiki differs from message boards because, while all the history of wiki edits is saved, it is not all displayed; therefore, only the most recent or updated information remains. In the case of large-scale wikis, such as Wikipedia, the edits by multiple users generally results in only the "factual" information remaining on the page. The collective group decides the most acceptable information that will remain for others to see after it iteratively undergoes multiple revisions. While wikis have been implemented in smaller design groups and in the form of mass-collaboration projects in the documentation of facts (i.e., Wikipedia), a wiki has not yet been extensively implemented for use by a large, distributed design team. The differences in using wiki for design activities versus knowledge documentation are primarily that design incorporates the formulation of many different concepts and rational decision-making techniques to focus ideas. In design, however, there is no single "correct" solution to the problem.

2.2 Current State of Wikis in Engineering Design. The web-based nature of wikis allows for a broad range of opportunities to enhance collaboration and communication among design teams, especially geographically dispersed teams. Studies of wiki use in industry show that wikis can support collaborative design activities; however, drawbacks in the current state of wiki technology and wiki use inhibit more efficient use of this technology in design [38]. Two barriers to capturing information during collaborative work have been identified by Arias et al.: "(1) individuals must perceive a direct benefit in contributing to organizational memory that is large enough to outweigh the effort; and (2) the effort required to contribute to organizational memory must be minimal so it will not interfere with getting the real work done" [39]. With the existing wiki technologies, it appears that the gap between contributing to the organization and effort required to utilize the tool has not been minimized enough for people to feel that the input effort required is worth the resulting output. To improve the usability of wikis for design, a better understanding of these shortcomings is required.

Wikis are not only becoming increasingly popular in industrial applications as tools for supporting design but also as teaching tools in higher education, especially design education. At Stanford University, Chen et al. explored how the use of wikis and weblogs in combination with the pedagogic approach of folio thinking in project-based design courses can have a positive effect on students' knowledge and skills in engineering design [35]. Survey and interview results demonstrated that wiki and weblogs helped students to become more aware of their learning progress and design skills, attesting to the potential suitability of wikis as tools for design education. While this particular study focused on the use of wikis and weblogs as a pedagogic tool, it provides strong support for improved design learning and enriched experience through wiki use.

In a product development course at the University of Karlsruhe, students were provided a wiki to use for design documentation during the course. The wiki was intended to serve as an aid in "sharing and distributing knowledge, using knowledge, and preserving knowledge" [40]. The study, focused mainly on the use of wiki for knowledge management, determined that wikis are suitable for documentation within the product development processes. A similar study at the University of Strathclyde, focused specifically on the sharing of information and resources in a design course, found that students preferred to browse the wiki structure to find information rather than to use keyword searches [41]. These studies concentrated on the documentation of information but did not address in depth the sharing of ideas and concepts using the wiki.

Wodehouse et al. presented a study of groups of third year design engineering students who were using a particular wiki engine, TikiWiki, for solving a rapid design task in ten teams of four students each in 6 weeks [42]. Results showed that using the wiki helped students to generate product concepts. The teams who interacted more with stored information in the wiki generally achieved better results in the design project, even though transferring concept information into the digital domain was identified as a disadvantage that caused additional effort for the students. It was also suggested by the authors that adding and adjusting special wiki features for design and an improved understanding of information management in design processes may help to increase the usefulness of wikis for design and design education. Because they are still an emerging technology, the implementation of wikis for smaller groups such as engineering design teams has been more gradual than that of mass-collaboration wiki platforms such as Wikipedia.

Wikis are also becoming widely adopted in higher education settings other than engineering design. Raitman et al., for example, explored the use of wikis in Computer and Information Technology course work at Deakin University in Australia [43]. Survey results showed that most users reported that wikis generally support collaboration but many wished wikis to be easier to use and to provide more features. This implies that the usefulness of wikis for applications in industry and education may be significantly increased, but a better understanding of the processes and user needs for certain applications like design and design education is needed.

The collaboration and communication capabilities, the potential to serve as an interactive education tool, and the valuable documentation features make wikis an ideal platform for exploration in design team settings. There is, however, substantial room for improvement in wiki technology and usage, especially when customized for design purposes. A thorough analysis of current wiki use in design and a better understanding of the design activities that should be supported by wikis are needed to design new and improved design wiki features and to provide more specific usage recommendations.

Most existing studies on wiki technologies focus on the process of learning, and, to a lesser extent, on the processes of knowledge production. However, little research addresses the use of wiki technologies to examine the processes of innovation and decision-making or as effective tools for design processes and production. In contrast to expectations from the cues-filtered-out [44] or social cues [45] perspectives of computer-mediated communication (CMC), which suggest that CMC lacks the capability to support socio-emotional connections of groups, Flanagin found that students using collaborative technologies quickly establish norms of use and group behavior and report satisfying bonds and identification with members of their team [46]. In addition, wiki technologies provide the possibility of supporting the representation of tacit as well as explicit knowledge, and the facilitation of collaborative deliberations in a manner that changes, and presumably improves, the design process.

Thus, peer to peer communication tools, such as (1) chat-enabled wikis alongside more formal documentation, (2) emerging technologies for naturally capturing visual representations of knowledge (sketches and graphs), and (3) audio captures of interactive moments (revealing both tacit and shared knowledge), provide the opportunity to examine the emergence of explicit knowledge. This examination will also enable understanding the processes, technologies, structures, and systems that provide support to successful design communication and lead to creative, innovative, and quality product outcomes. Our studies comparing colocated and distributed teams provide an initial step toward this goal.

3 A Communication Based Framework for Analyzing Wikis in Design

It is through communication that roles are defined, ideas are generated and shared, decisions are made, and outcomes are produced; therefore, communication is an essential component of the engineering design process that merits additional research and understanding. With a framework for considering the intersection of communication and engineering design, a method for studying the effectiveness of using wiki as communication tool for design is presented. Three approaches for gathering and analyzing data include retrieving statistical information regarding the usage of the wiki, analyzing the content of the wiki (language/text), and requesting direct feedback from users via surveys, interviews, and focus group discussions.

Several advantages of using wiki for early design have been identified including its strong potential for multiple modes of communication; qualities of persistence (electronic storage with history of edits); the asynchronous nature of collaboration (allowing more time for reflection, thinking about contributions, and formulation of content); its relatively unstructured form (so that members can re-arrange data, add/delete information, etc.); and that it is highly conducive to iteration processes. To explore these advantages, in this study, we examine design interaction and communication among distributed teams using wiki technologies.

First, the wiki's relative lack of structure compared to other electronic media allows for dynamic modification, a critical component of early design. As explained by Arias et al., open software systems are an essential part of supporting collaborative design [39]. Design problems are ill-structured and ill-defined [21], and therefore, the computer systems for supporting design must be able to change over time as the design problems and contexts evolve. "By creating the opportunities to shape the systems, the owners of the problems can be involved in the formulation and evolution of those problems through the system" [39]. To meet this functionality, Arias et al. provides four principles for software to support collaborative design: (1) software systems must evolve; they cannot be completely designed prior to use; (2) systems must evolve at the hands of the users; (3) systems must be designed for evolution; and (4) evolution of systems must take place in a distributed manner [39]. Under these conditions, wikis provide a nearly ideal platform for an electronic collaborative design support tool. We employ two methods for evaluating the structure of the wiki: (1) an observation of the structure as it evolves through the design process and (2) a discussion with users to obtain their opinions about the structure. By reviewing the contents of teams' wiki pages at various stages through the design process, patterns may emerge among different teams in terms of optimal methods for structuring pages. A comparison of the wiki sites between different teams after the completion of a design project may provide valuable insight into the features and items teams find to be important.

Next, we examine the development of shared knowledge among team members, by using several modes of learning as the basis for assessment [47] including: (1) student perceptions of their understanding at different points in the design process; (2) a coding scheme to determine shared understanding; and (3) an analysis of weekly communication diaries. These techniques are used to analyze team wikis for content and to obtain feedback from users and provide valuable insight regarding shared understanding among teams.

Finally, usage statistics such as the number of edits per person, number of edits per day (or per time period), number of wiki pages, number of page visitations, number of internal and external links, number of file types used, bounce rate, average time per page, and number of times certain words are used to provide meaningful data for understanding the ways team members utilize wiki technologies during design. Site usage statistics and survey questionnaires were also used to identify the barriers encountered among design teams while recording information or communicating ideas over the wiki.

4 Study

4.1 Methods. To investigate the impact of the wiki on engineering design, an exploratory study was conducted at the University of Karlsruhe, where a wiki was provided for over 500 Mechanical Engineering students enrolled in a Machine Design course. A survey consisting of 39 questions including three open response questions was administered. The main results are summarized here as follows:

1. In general, students who found the use of the wiki to be simple (Q9) and who agreed that the issues concerning the wiki were easy to resolve (Q10) also found the wiki to be a useful tool for this engineering design project (Q37) ($p < 0.0001$).
2. The survey results also support the use of wiki for collaboration and team/group work. Based on the responses, the teams who had more than one person using the wiki (Q26) found it a useful tool (Q37), while teams who reported only one person managed the wiki did not find it as useful for the project ($p = 0.0129$). This supports our hypothesis that wiki can be a useful tool for collaboration in design.
3. Finally, students who felt that the wiki enhanced communication among their team (Q17) were more likely to agree that the wiki was a useful tool for this engineering design project (Q37) ($p < 0.0001$). This finding also provides the support for the idea of using wiki as a collaborative design tool.

These results were used to refine a subsequent study conducted by the following academic term at Purdue University. Following this preliminary study, a wiki hosted by GlobalHUB™ [48] was implemented in a graduate level Product Design course in the School of Mechanical Engineering at Purdue University to provide students with an online platform for communication, documentation, and sharing of resources. Feedback was collected from the students using interviews and e-mail during the course of the semester, and a survey was conducted to determine the utility and usability of the wiki for product development in an academic setting. The full list of survey questions utilized in the University of Karlsruhe study and the Purdue University study may be viewed on the Computational Design and Innovation website.[2]

The Purdue Product Design course was divided into 17 design teams (ranging from two to four members each): ten teams were geographically distributed within a time zone, and seven teams were colocated. During the course, the students identified product opportunities and developed a proposal for a product design. They ascertained user needs using Kawakita Jiro (KJ) and Kano analysis and various customer surveys. The needs were translated to form a House of Quality using Quality Function Deployment (QFD) along with benchmarking of competing alternatives. The House of Quality was then used to perform lean QFD and find the most important functions of each team's product. The teams also used Theory of Inventive Problem Solving (in Russian) (TRIZ), Design for Assembly, Mathematical Modeling, and other methods to solidify the final derivation of their products.

Each team maintained its own wiki, and each team member was asked to update the wiki as appropriate. In effect, the wiki replaced the traditional paper logbook and was treated as the equivalent of a collaborative design notebook. The instructor examined the wiki biweekly and after grading assignments to

[2]https://engineering.purdue.edu/PRECISE.

provide feedback and comments. The wiki sites were also used as a medium for communication among the distributed teams.

To examine and analyze patterns among the different teams, they were divided into two subgroups: distributed and colocated. We predicted that distributed teams (lacking the ability to easily meet face-to-face) would be more likely to use the wiki to convey ideas to team members. The colocated group was divided into on-campus and off-campus groups. These divisions were made because the two off-campus teams that were colocated performed at the same standard as the rest of the distributed teams. Their wiki was of higher quality than that of the on-campus teams. On a posthoc basis, the distributed teams were also divided into three subgroups: functional, dysfunctional, and top scoring. Based upon negative peer reviews that resulted in altered individual grades, three teams were labeled dysfunctional, reflecting an inability to perform successfully as a team. Each individual rated the contributions of other members and themselves at the end of the course. We used the peer review and especially unanimously negative ones to scale the grade of dysfunctional team members, who were a small percentage in the entire class. The results for these teams were separated from the functional teams in order to observe the differences between teams. In addition, the top scoring (functional) team was separated from both the functional and dysfunctional groups based upon team performance. The top team's performance was above and beyond the other teams, causing it to be a statistical outlier.

Usage statistics were collected and analyzed through GlobalHUB™ [48] and Google Analytics for each team's design wiki. Measures included number of page views, bounce rate, total number of pages, average time per view, number of submissions, and number of uploaded files. These measures were analyzed to observe patterns between the groups and subgroups. In addition, wiki usage data were compared with team project grades to examine emergent patterns that might predict team performance.

In Sec. 4.2, we discuss the results of the survey and wiki usage statistics.

4.2 Results. Examining wiki use and development among teams illustrated some interesting factors about collaboration in engineering design teams. First, the wiki tool proved a comfortable environment for most students: although many had no prior experience with wikis before the course, most reported comfort in using the technology at the end of the course (Figs. 3 and 4).

Participation among team members in contributing to the wiki varied depending upon team type. Due to the asynchronous nature of the wiki, we expected that individuals who may be reluctant to speak in face-to-face settings would be more likely to contribute and share their ideas through the wiki. While we did not test this directly, we did observe that one or two members on each team were responsible for the majority of the submissions on the wikis based upon a calculated submission equity index. However, in all but two teams, members were fairly consistent in participating through wiki contributions to the main page: Each member submitted at least four contributions to the wiki.

The utility of the wiki tool for supporting design processes was also assessed. Notably 96% of the distributed team members reported that the wiki was a useful class project tool, compared to 57% of colocated teams (Fig. 5). However, the distributed teams reported difficulties with the wiki tool's capability to serve as an effective synchronous communication medium because it lacked an integrated instant communication device (see Fig. 6). However, even though the wiki lacked synchronous communication capabilities, distributed team members did agree that it enhanced communication among team members. This was not true for the colocated teams (Fig. 7).

Distinctive patterns in the usage of a wiki suggest additional differences in how colocated and distributed teams use the tool. For example, the distributed teams uploaded their thoughts on the wiki prior to synchronous verbal discussions via telephone or internet conferencing, while the colocated teams discussed ideas face-to-face and uploaded units of their discussion either during or after the team meetings. Thus, the wiki was used more as a documentation tool for colocated teams rather than as a communication tool, likely because of the ease with which team members could discuss ideas in face-to-face settings. Because the distributed teams uploaded their ideas prior to their verbal discussions, a shared basis for understanding among team members had been

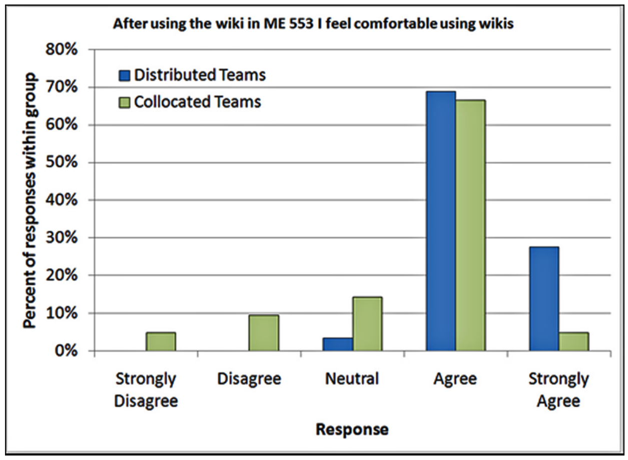

Fig. 4 Comfort using wikis after ME553

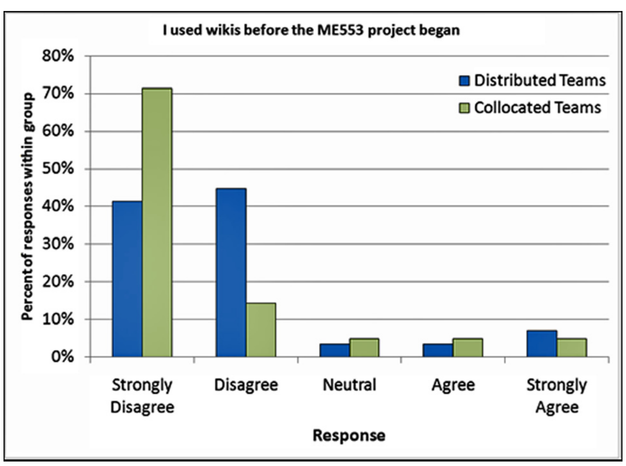

Fig. 3 Experience using wikis prior to ME553

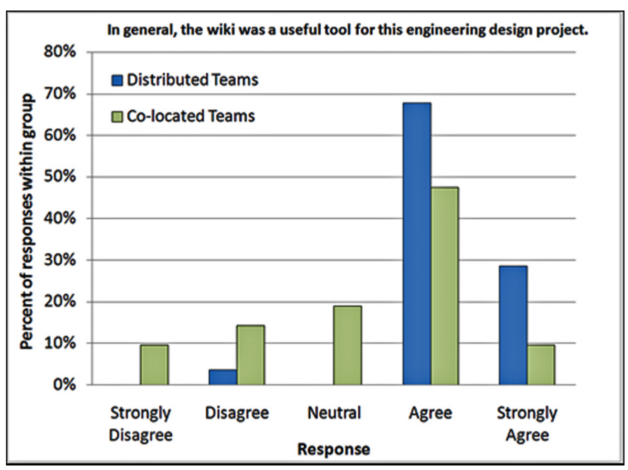

Fig. 5 Usefulness of wiki for communication

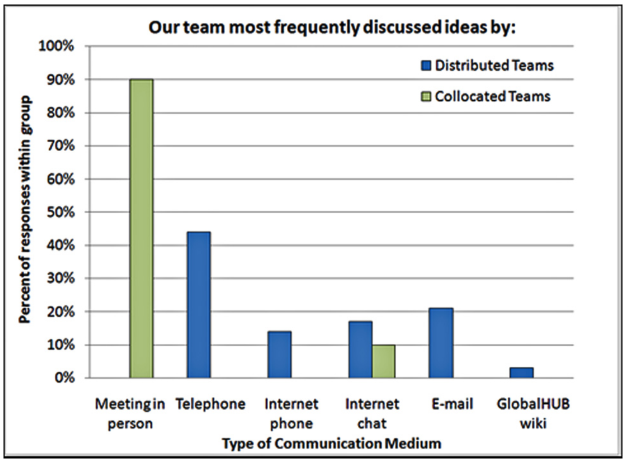

Fig. 6 Methods of communication to discuss ideas

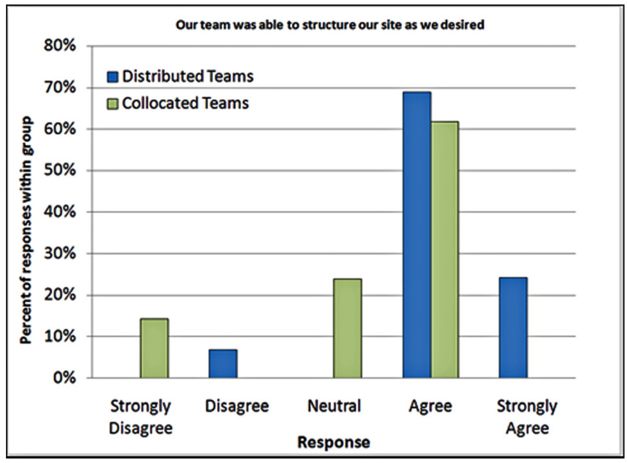

Fig. 8 Ease in structuring wikis

established, and more was accomplished during a shorter time in the meetings. Related studies [49] also attribute some of the effectiveness of distributed teams to the fact that the properties of the communication technology force members to focus on work, rather than play, resulting in a greater efficiency.

Colocated team members agreed that the wiki was most valuable as a documentation tool. Many of these students reported the wiki was valuable in providing a single location to store documents pertaining to the project and eliminated the need to search for and consolidate relevant data in multiple notebooks or computers at the close of the project.

Furthermore, the way information was organized and structured was distinct as well. For example, students frequently mentioned that the first thing they did as a team was to develop a structure for the wiki for posting data. Very few students reported difficulty in structuring the wikis (see Fig. 8). Although no formal or required structure for the wiki sites was provided, distinct structures emerged from the teams. We analyzed the wiki structures for all 17 teams and assessed the ease of navigation, the number of levels, and the complexity level for all team wikis (Table 1). In addition, to assess relationships of structure with team performance, the average instructor ratings for each team are included. However, there was no apparent correlation between site structure (or complexity) and team performance. If anything, it appears simpler structures may have higher team performance scores.

In general, participation of distributed teams was much greater and the contributions were of higher quality, as measured by the three professors' expert judgment, compared to colocated teams.

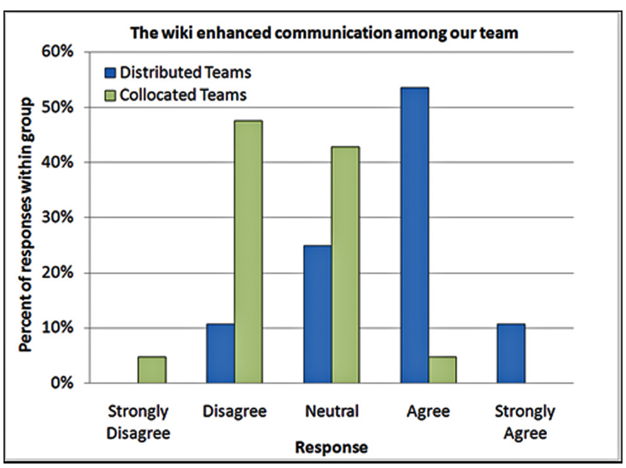

Fig. 7 Usefulness of wiki for communication

For the distributed teams, the division of tasks with people having different roles in the team was reflected in the wiki structure. A summary of the usage statistics for the design wikis of each team verifies these observations. The quality of the off-campus team's projects was higher than that of the on-campus teams based upon overall project performance grades. However, it should be noted that the off-campus students typically had greater industry experience than the on-campus students, and these experiences included teamwork, design, and project planning experiences that could influence both project selection and outcomes. In addition, the number of files uploaded and the average time spent viewing pages was higher for the off-campus students, supporting this observation of greater and more uniform participation among the team members. The submission quality index was also higher for distributed students. This is possibly explained by the likelihood that the colocated teams are more likely to discuss their projects face-to-face and have a designated team member to collect and post the content for the wiki. In fact, 48% of the colocated team members reported that their wikis were managed by only one person compared to 31% of the distributed team members.

Interesting patterns in wiki usage also become evident when comparing page-view data over the entire course (Fig. 9). As expected, wiki activity tended to spike around key assignment due dates during the semester. However, the higher performing teams tended to have extended times of heightened activity associated

Table 1 A summary of wiki structures used by design teams

Team	Layers	Complexity	Ease of use	Complexity level	Grade
1	2	Simple, files/pages level 2	5	2	90
2	3	Seminested	4	3	85
3	3	Fully nested	4	5	70
4	2	Simple, no files	3	2	80
5	3	Simple, third level	5	2	85
6	3	Simple, main page relink	5	3	90
7	3	Simple, third level	5	2	95
8	3	Simple, third level	5	2	100
9	3	Adjacent page nested	5	4	85
10	5	Fully nested, fifth level	4	5	90
11	2	Simple, no files	4	2	80
12	3	Simple, third level	5	2	90
13	4	Simple, fourth level	4	3	72.25
14	3	Simple, third level	3	2	76.5
15	2	Simple, files/pages level 2	5	2	72.25
16	2	Simple, one page, files only	5	1	76.5
17	2	Main page and final file	5	1	68

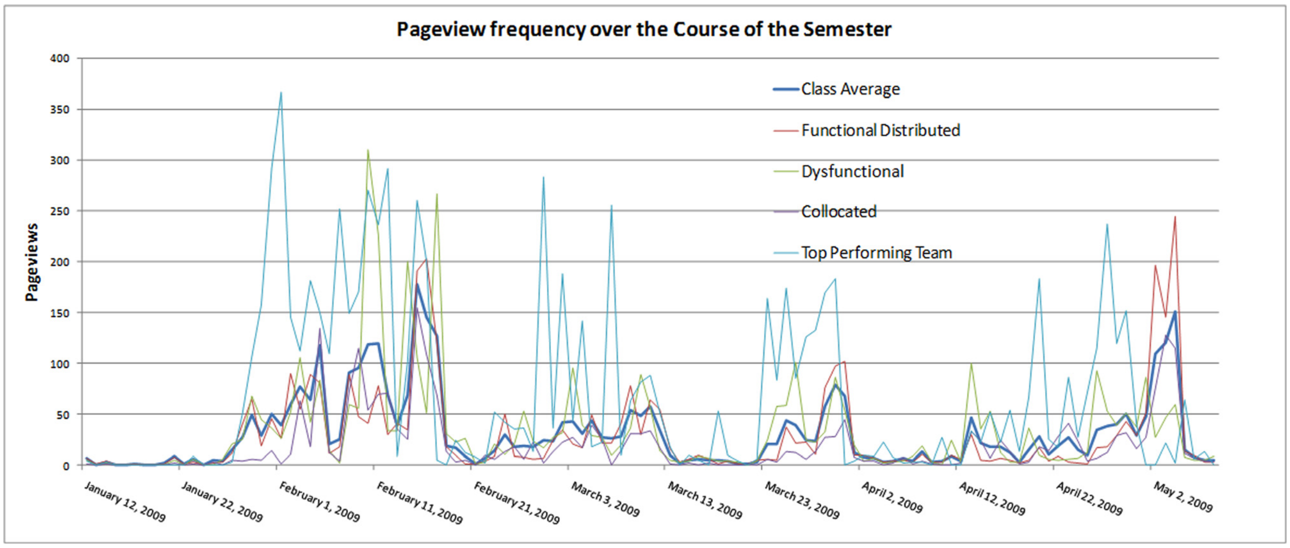

Fig. 9 Page-view frequency for leading subgroups of the semester

with assignment deadlines. The top performing team (distributed) had the longest times of heightened activity, using the wiki both earlier and up until assignment deadline. This extended activity could also reflect that the wiki was used more to communicate and compile their assignments as well, compared to the colocated teams that appeared to communicate and do work off-line and then upload final results to the wiki. Figure 10 provides an illustration of average page-view frequency over the semester for the top performing, colocated, and distributed teams in relationship with course deadlines.

In addition, team performance was plotted against the average number of page views, the average time viewing pages, and the total amount of time spent on the wikis. In general, higher page views and time on wiki correlated with higher team performance. The colocated teams spent less time on the wiki than the distributed teams, supporting the prediction that the colocated teams worked primarily outside of the wiki and used them as documentation centers, rather than communication or collaborative mediums. In addition, the dysfunctional (off-campus) teams spent equivalent time on the wiki as functional teams but differed in a

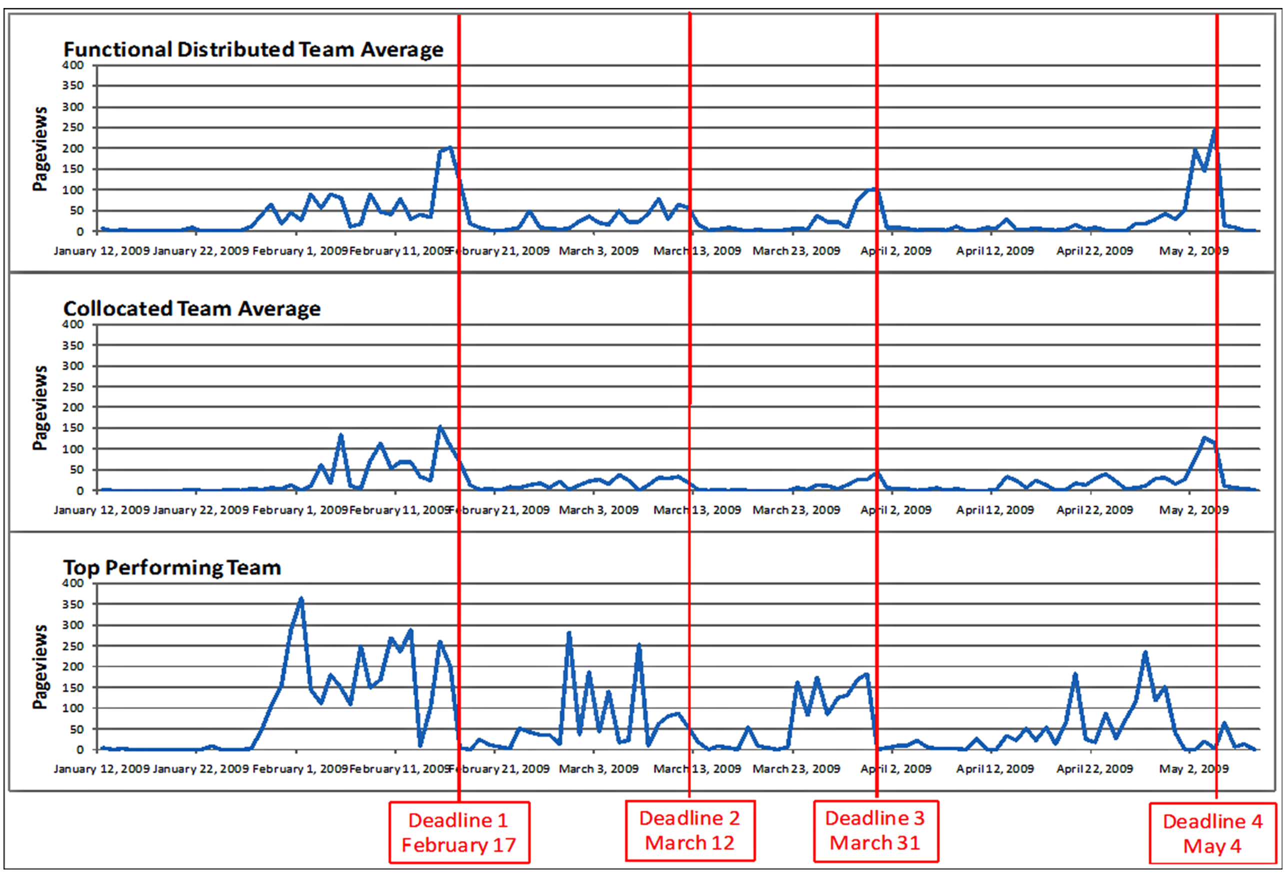

Fig. 10 Page-view frequency with respect to assignment deadlines

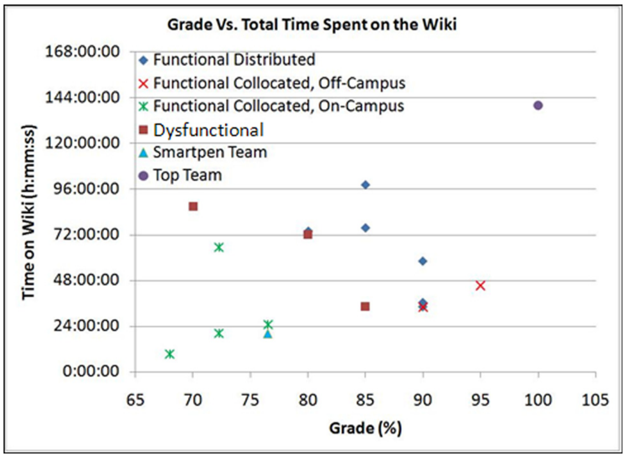

Fig. 11 Total time on wiki and performance

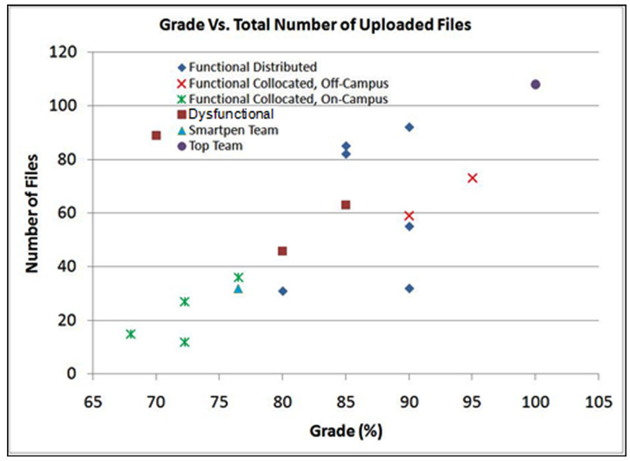

Fig. 13 Relationship of files uploaded to performance

key factor: noncontributing members performed lower than contributing team members, reflecting greater disparities (or inequities) in contribution to the project (see Figs. 11 and 12).

Results from our previous research [50] indicate that students found it difficult and time consuming to record conceptual design ideas because of the formatting required to upload images into the wiki. Sharing sketches required that students sketch on paper, scan the sketch (or take a photograph and upload it to the computer), import/upload it into the wiki, and then adjust the sizing [50]. To upload many sketches and track conceptual designs, this process can be quite cumbersome and time consuming, particularly when ideas and designs are still emerging during the collaborative process. Therefore, although it is relatively easy to use for documenting text, wikis are not yet an efficient means for documenting other design information such as sketches, tables, block diagrams, function diagrams, etc.

The survey results also assessed additional technologies used for team communication and collaboration. E-mail is a fast and efficient means of communication, but it can be difficult to quickly find a specific piece of information because communicated messages are dispersed among multiple and separate e-mail files. Integrated multimodal communication such as tablets with wiki's integrated with e-mail and synchronous communication capabilities could reduce barriers to communication. To this point, however, this potential has yet to be fully harnessed to augment and support collaboration and communication during early design activities.

We used a method for sketching called 6-3-5 method, where each member progressively builds on the previous members sketch. This is particularly suitable for asynchronous communication such as the wiki. The respondents can take more time allowing for reflective thinking. We found that the overall quality and number of sketches were similar for the distributed and colocated teams.

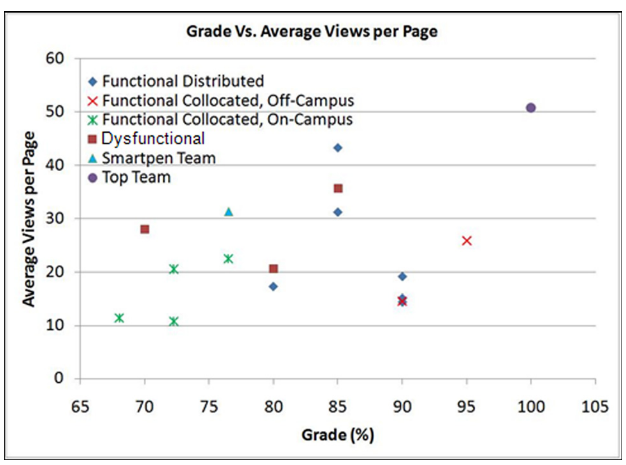

Fig. 12 Average views per page and performance

We also examined the content of wiki contributions in terms of file types uploaded, to determine whether complexity in content matter contributes to team performance and success. The relationship between the number of file-types and total number of files uploaded was analyzed against team performance. In general, performance increased when the team used a greater number of file types (see Fig. 13) and also variety (such as ppt or pdf). Further analysis of how this is affected at individual and team levels is required before we can determine why this occurs. In addition, the content embedded in the variety of file types also has to be analyzed.

5 Discussion and Concluding Remarks

The results of this study indicate that the distributed teams value and use design wikis more than the colocated teams. Specifically, we found that the distributed teams were more likely to use the wiki as a design tool, distributed the use of the contributions among team members, and used the tool earlier in the design process, than the colocated teams. In contrast, the colocated teams were more likely to use the wiki as a documentation tool, later in the design process, and with only selected team members contributing. Furthermore, team performance increased with time spent on the wiki and with increased volume and variety in content contributions. In addition, the wiki structures created by distributed teams were better on the average than those of colocated teams.

The high performance and positive feedback on the benefits of the wiki from the distributed teams confirm that a wiki environment is an effective collaboration tool in early design processes. Distributed teams found the wiki more broadly useful for collaboration and documentation. In stark contrast, the colocated teams perceived the wiki more as an impediment to team communication. For distributed teams, the wiki enabled more equal participation of team members, and social distance did not appear to hamper performance. However, because the distributed team members had an average 2–3 year of industry experience with team work, project management, and design, the improved performance of the distributed teams cannot be fully attributed to the effective use of the wiki.

Although current wiki technology is not yet sufficient to allow exclusive use of wiki as a support tool for collaborative design among distributed teams, the underlying concept provides a strong basis for the development of future online tools. Wikis are easily accessible and provide a flexible platform for recording and sharing information among collaborative teams and can be particularly useful during early design phases. They have a strong potential to facilitate and improve communication between design team participants and provide a viable means for enhancing shared understanding, especially when frequent face-to-face communication is not feasible.

Future research will focus on further evaluating wikis as an effective tool for communication in engineering design by considering the means in which they advance shared understanding among participants during early design. We also plan to develop a measure of site complexity using a site mapping program, to determine if it is another indicator of performance level.

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