Human-centered design of a distributed knowledge management system

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Abstract

Many healthcare technology projects fail due to the lack of consideration of human issues, such as workflow, organizational change, and usability, during the design and implementation stages of a project’s development process. Even when human issues are considered, the consideration is typically on designing better user interfaces. We argue that human-centered computing goes beyond a better user interface: it should include considerations of users, functions and tasks that are fundamental to human-centered computing. From this perspective, we integrated a previously developed human-centered methodology with a Project Design Lifecycle, and we applied this integration in the design of a complex distributed knowledge management system for the Biomedical Engineer (BME) domain in the Mission Control Center at NASA Johnson Space Center. We analyzed this complex system, identified its problems, generated systems requirements, and provided specifications of a replacement prototype for effective organizational memory and knowledge management. We demonstrated the value provided by our human-centered approach and described the unique properties, structures, and processes discovered using this methodology and how they contributed in the design of the prototype.

Keywords: Human-centered computing; Organizational memory; Knowledge management; Collaborative; Groupware; Information systems; Design; Ethnographic; Project lifecycle

1. Introduction

A large number of healthcare information technology projects fail. Many of these failures are not due to flawed technology, but rather due to the lack of systematic considerations of human issues in the systems requirements and specifications processes. In other industries such as aviation, nuclear power plants, automobiles, and consumer software and electronics, human-centered design is commonly practiced. In healthcare, however, the culture is still to train people to adapt to poorly designed technology, rather than to design technology to fit people’s characteristics. Systematically incorporating human-centered design is necessary for successful development of information systems that increase efficiency, productivity, ease of use, learning, user adoption, retention, satisfaction, and decrease development time, support and training costs, and medical errors. The study of human–computer interaction (HCI) has made significant contributions to the design of user-friendly systems. However, the primary focus has been on the design of the interfaces between systems and users, such as usability testing, and not the deeper structures that are fundamental for the design of truly human-centered systems [1]. We argue that human-centered computing goes beyond the representations in an
interface, but also includes users, functions and tasks that are fundamental to the processes at large.

In this paper, we describe the application of a human-centered design methodology called human centered distributed information design (HCDID) [1] to generate the systems requirements and specifications for a web-based knowledge management system for biomedical engineers (BMEs) in Mission Control Center at the NASA Johnson Space Center. The HCDID methodology was developed with the aim of providing systematic principles, guidelines, and procedures for the design of complex, highly efficient distributed human-centered information systems. In this paper, we will first describe the HCDID methodology. We will then describe the Project Design Lifecycle and how it is integrated with the HCDID methodology. In this section we will demonstrate how the HCDID methodology and the Project Design Lifecycle are used in the development of a web-based knowledge management system for NASA’s BMEs. In the discussion and conclusion sections, we will discuss the value of our human-centered methodology in the design of distributed information systems.

2. Methodology

2.1. Human-centered distributed information design

The human-centered distributed information design (HCDID) methodology considers human-centered computing at the levels of users, functions, tasks, and representations. As shown in Fig. 1, the components on the left are multiple levels of analyses for single-user human-centered design. The user analysis level contributes to each of the levels of functional, task, and representational analysis. The components on the right represent the additional analysis needed for designing distributed human-centered information systems. The component at the bottom represents the products of functional, task, and representational analyses. For each level of analysis, the HCDID methodology allows the researchers to employ several, alternate specific methods [1].

HCDID is based upon the principles of distributed cognition. The core unit of analysis is the functional system which is composed of human and artificial agents and their relations which are distributed across time and space dimensions [2–9]. Distributed cognition helps determine which features of the activities or artifacts are relevant for the efficiency of task performance and which are necessary for the activity to continue to perform well. It can identify complex interdependencies between human and artificial agents that occur in collaborative work environments and thus give the researchers a better understanding of why simple breakdowns in communications and interactions between them can have such serious and significant consequences [10].

HCDID provides a framework that addresses the distributed social, cultural, organizational interactions, and cognitive issues involved in designing information...
technologies within a complex distributed, collaborative environment. The following describes the components of the HCDID methodology.

2.1.1. User analysis

User analysis is the process of identifying the characteristics of existing and potential users, such as expertise and skills, knowledge bases, educational background, cognitive capacities and limitations, perceptual variations, age-related skills, time available for learning and training, frequency of system use, etc. [11,12]. For a health information system, different users such as installers, administrators, nurses, physicians, registration personnel, laboratory technicians, billing staff, and patients may use different components of the system. Different users may also have different levels of understanding of the same component of the system, such as beginners, novices, and experts. User analysis helps us to design information systems that have the right knowledge and information structure that match those of the users.

2.1.2. Functional analysis

Functional analysis is the process of identifying critical top-level domain structures, goals, and inherent properties of the work domain that are largely independent of implementations. It is more abstract than task and representational analyses because it does not involve details of task processes and representation details. For a distributed system, functional analysis also identifies the artifacts as well as artificial and human agents of the system, their interrelations and constraints, and their essential roles. For a knowledge-rich domain such as medicine or aviation, functional analysis requires extensive domain knowledge and a deep understanding of domain structures.

2.1.3. Task analysis

Task analysis is the process of identifying the procedures and actions to be carried out and the information to be processed to achieve task goals. One important function of task analysis is to ensure that only the necessary and sufficient task features that match users’ capacities and are required by the task will be included in systems specifications. Extra fancy features that do not match users’ capacities or are not required by the task will only generate extra processing demands for the user and thus make the system harder to use. For a distributed cognitive system it is important to perform a distributed task analysis that identifies the interactions among human and artificial agents. This perspective may also help identify how multiple users interact with the same data. The theory of distributed representations developed by Zhang and Norman [4,5] can be used to analyze the distribution patterns of information among human and artificial agents [13]. Task analysis can identify overlooked tasks, the relative importance of tasks, the overlapping of task information, the grouping of functions, the relation to user analysis, and so on. It can also pinpoint the bottlenecks or choking point of the task where special design has to be considered.

2.1.4. Representational analysis

Representational analysis is based upon a robust phenomenon called representational effect [5,14]: different representations of a common abstract structure or process can generate dramatically different representational efficiencies, task difficulties, and behavioral outcomes. It is the process of identifying an appropriate information display format for a given task performed by a specific type of users such that the interaction between users and systems is in a direct interaction mode [5,15–17]. With direct interaction interfaces, users can directly, completely, and efficiently engage in the primary tasks they intend to perform, not the housekeeping interface tasks that are barriers between users and systems [18,19].

The form of a representation can influence and sometimes determine what information can be easily perceived, what processes are activated, what can be derived from the representation. For a complex novel task, some portion of the task space may never be explored and some structures of the task may never be discovered without a change in representation.

The end products generated from the methodology of HCDID are the contents for the systems requirements and specifications of human-centered distributed information systems. Examples of these contents include functional requirements, goal-subgoal relations, task structures and procedures, information flow dynamics, and task-specific, event-related, and context-sensitive information displays.

2.2. Project design lifecycle

A key advantage of the HCDID methodology is its practical application to a project’s design lifecycle. This Project Design Lifecycle is inherently iterative in nature and the theory and methods help to refine the products generated from each phase. For discussion purposes, we have placed the various components of the Project Design Lifecycle into specific phases. We recognize that these components occur throughout each phase and may not be limited to any specific phase. It is important to note that evaluation is a key step throughout the entire Project Design Lifecycle. The following describes how the HCDID methodology is incorporated into the various stages of the Project Design Lifecycle (see Fig. 2).

2.2.1. Phase 1: Data collection and analysis

This phase seeks to discover key aspects about the problem domain, their users, functions, and tasks.
During this phase, data collection and the user, functional, and task analyses in the HCDID framework are typically carried out. The products of this phase is the identification of issues which are then framed within an organizational memory and knowledge context.

2.2.2. Phase 2: Systems requirements

The identification of the issues provides the building blocks to help define the systems requirements. Functional analysis is the primary analysis during Phase 2. The products of this phase, the systems requirements, will then be mapped to provide the specifications in Phase 3.

2.2.3. Phase 3: Specifications

In this next phase, after the systems requirements are mapped to the specifications, mockups are created. Representational analysis from the HCDID methodology plays a key role in helping to generate design alternatives. Different representations of a common abstract structure or process can generate dramatically different representational efficiencies, task difficulties, and behavioral outcomes. In addition to representational analysis, task analysis is also performed to supplement representational analysis. Evaluations are continued throughout this phase and the systems requirements and specifications are further refined and used for designing the prototype in Phase 4.

2.2.4. Phase 4: Prototype

In this phase, a working prototype is developed from the mockups developed in Phase 3. Representation analysis is conducted to help generate the user interface and to guide which representation is suited for each task. Usability testing is also performed throughout this phase. After the completion of Phase 4, the cycle reiterates.

3. Case study: biomedical engineering domain at NASA

In this section, we will describe a case study where we applied the HCDID methodology and the Project Design Lifecycle to design a human-centered knowledge management system. We will first describe the domain of the Biomedical Engineers and the critical issues that are central to human-centered information systems. Then we will describe the methods, procedures, and results of applying the HCDID and the Project Design Lifecycle in the BME domain.

The task domain for the current study is the Biomedical Engineer console at Mission Control Center, NASA Johnson Space Center, Houston, Texas. In this domain, the primary roles are: (1) the Console BMEs who are responsible for providing the technical and operational support for medical operations activities involving the astronauts on the International Space Station; (2) the BME Liaisons (BME-L) who are responsible for tracking and working on issues, and helping to reduce the interruptions to the Console BME; and (3) Flight Surgeons (FS) who have the primary authority for the health and safety of astronauts.

Astronauts in a space station are to some extent like patients in an intensive care unit (ICU): their living environment is off nominal; their health conditions are monitored and evaluated continuously; their lives are supported by a large number of complex devices and equipment; they are subject to a lot of factors that may threaten their lives. But there is also a significant difference between a space station and an ICU: emergency procedures are very limited in quality and quantity in a space station when a serious contingency occurs during a mission. Thus, it is imperative that there be good, timely support from medical operations personnel, including biomedical engineers and flight surgeons. This support falls into two categories: (1) handling medically relevant events such as illness or environmental contamination; and (2) tracking crew health parameters to enable early detection of possible problems. For the first category, a number of procedures and guidelines exist that are located both electronically and on paper.

For the purpose of crew monitoring, a huge amount of medical and related data is generated and collected for every astronaut before, during, and after each flight. These data include physical exams, fitness evaluations, laboratory tests, in-flight and off-flight periodic health evaluations, private medical conferences, health condition monitoring during extra-vehicular activities, radiation dosimetry, toxicology and microbiology monitoring, and many more. Medical support of a mission crew will require acquisition, transmission, distribution, integration, search, and archiving of significant amounts of data and information sources [20].
The Console BME role requires complex interactions and exchanges of information among people with multiple roles throughout various disciplines. These interactions and communications occur both synchronously and asynchronously and are distributed across space and time dimensions. Personnel may be located within NASA’s Mission Control, at other NASA facilities located throughout the United States and aboard the space shuttle or the International Space Station. Data are transmitted through multiple media, such as voice loop, telephone, video conferencing, fax machines, computers and face-to-face interactions, and are subject to changes during the process. A key technology for communication and information exchange with the BME domain is the voice loop. Voice loop is an auditory groupware technology that supports synchronous communication on multiple channels among groups of people who are spatially distributed. The Console BMEs spend approximately 60% of their time passively listening and 40% participating in the communications while performing other activities at the console.

Personnel involved in this information flow process typically function in a multi-tasking, interruption-laden workplace with access to non-user friendly information sharing tools. Sharing and communication of individual and group knowledge among the BMEs and across other related domains are essential components of this process. These components become even more critical during collaborative group problem solving. While other domains such as aviation or healthcare exhibit similar characteristics, the added dimension of part of this domain, the International Space Station, being physically located in space, makes the task of knowledge management even more challenging. Attempts to create and manage organizational memory have resulted in bulging information repositories with disjointed databases that lack structure and search capabilities which make information retrieval frustrating, and at times, unsuccessful for users.

3.1. Organizational memory and knowledge management

Designing information systems’ infrastructures for the capture of organizational memory and the distribution of this knowledge across an organization requires not only an in-depth understanding of the numerous technical knowledge management activities, but also, more importantly and often omitted, an understanding and inclusion of the social, cultural, organizational and cognitive aspects that not only occur within an individual or group of individuals but also occur across individuals and artificial agents.

The use of information technology to support organizational memory and subsequently enhance knowledge management has been examined in several studies [21–24]. The majority of information technology has been designed to enable knowledge management activities that target the capture of data and information, as opposed to harvesting knowledge itself [25]. Davenport describes knowledge management as the identification, acquisition, development, dissemination, utilization, and preservation of knowledge in the enterprise and acknowledges that knowledge management is proving to be difficult to manage and has been shown to be resistant to reengineering and process innovation [26]. Information technology is primarily used to support formal knowledge management in the form of conventional database management systems, data warehouses and mining tools, intranets/extranets, and groupware with disregard to informal knowledge and the underlying processes [27]. Although information science research has provided a sound, technical basis for understanding the fundamental process of information management and retrieval, it does not address the unique social, organizational and cognitive issues inherent within a distributed work environment. In the rest of Section 3, we will describe the processes and the results of applying HCDID and Project Design Lifecycle to design a human-centered knowledge management system with a focus on addressing the issues of organizational memory.

3.2. Phase 1: Data collection and analysis

Although the four phases of the Project Design Lifecycle are all important, due to the limit of the space available for this article, we will focus on Phase 1, which lays the foundation for the design. For the four types of analyses in HCDID, we will focus on functional analysis. We consider this the most important analysis because a product designed without the identification of the abstract structure of a domain is doomed to have many usability problems.

3.2.1. Data collection methods

Ethnographic techniques were first employed for the collection of data. Ethnographic studies provide information for the systems design process and contribute to producing insights that sometimes contradict conventional thinking usually employed in systems design [28]. Ethnography also complements the proposed human centered distributed information design methodology by applying the principles of distributed cognition to the design of specific technologies within a domain.

3.2.1.1. Live observation. The intense, time-pressured, data intensive nature of a Console BME shift handover was chosen for observation. This activity provided an opportunity to observe the interactions between two or more Console BMEs performing a mixture of both routine and non-routine activities as well as handover activities. Two researchers conducted the observation using a
video camera. One operated the camera while the other took written notes. Data from a live observation of the Console BMEs conducted by one of the researchers a year earlier was also used in the distributive cognitive analyses.

After conducting the observation, the tapes were analyzed. MacSHAPA [29], an exploratory sequential data analysis software application, was used to perform both qualitative and quantitative analyses. The tape contents were initially chunked into broad units such as when the BMEs were involved in performing tasks of searching for information that was prompted by a phone call. This was then further decomposed into smaller, defined basic units such as activities. Components of the activities are shown in Table 1.

Each activity was time stamped to include minutes and seconds. Corresponding data to the observation timeframe obtained from the Operations Issue Tracker and the BME Log Notes was entered into MacSHAPA. Focusing on the information flow and the components of the activities, the activities were encoded as predicates (Table 2).

Various analyses were performed and data on durations, transitions, timelines, content analysis, cycles, lags, and comparisons were obtained.

3.2.1.2. Document review. Documents that are routinely used and accessible by the Console BMEs were reviewed and studied by the researchers. These documents were available in paper and electronic formats. The researchers conducted various information retrieving searches in the electronic documents. Paper copies of the documents were located in binders either in a bookshelf directly behind the Console BMEs or distributed throughout the console environment.

- **Operations issue tracker.** All issue malfunctions, work-arounds, and resolutions are documented and tracked in the Operations Issues Tracker document by the BME Liaison. The Console BME contacts the BME Liaison about any issues or problems that occur while on console. The Liaison makes contact with the necessary personnel and “works” the issues providing feedback to the Console BME. The Console BME documents these interactions in the BME Log Notes. The tracker is updated daily, posted on an intranet website by the BME Liaison and is available for reference by the Console BME.

- **International space station (ISS) Log Notes.** The ISS Log Notes is a text document that provides a method of reconstructing the activities of the BME on console. This includes providing information to the oncoming Console BME(s) during shift handover, for postflight/operations analysis and to provide a database for contingency or failure analysis. ISS Log Notes were reviewed for 4 days prior and 3 days after the observation.

- **Operations manuals.** Standard operating procedures to support the job responsibilities of the BMEs, as well as all personnel involved with Medical Operations, are located in several operations manuals.

3.2.1.3. Interviews. Ten face-to-face, telephone, and email interviews were conducted with the Console BMEs, BME Liaisons and other NASA personnel such as BME trainers and engineers who are associated with this discipline. Requests were made for volunteers who were representative of the user types in this domain.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Activities encoded in MacShapa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activities</td>
<td>Components</td>
</tr>
<tr>
<td>Agent</td>
<td>BME, FS, and flight director (human or artificial)</td>
</tr>
<tr>
<td>From</td>
<td>Initiating agent</td>
</tr>
<tr>
<td>To</td>
<td>Responding agent</td>
</tr>
<tr>
<td>Action</td>
<td>Talk, type, write, monitor, and search</td>
</tr>
<tr>
<td>What</td>
<td>Topics</td>
</tr>
<tr>
<td>Where</td>
<td>Place where activity occurred</td>
</tr>
<tr>
<td>When</td>
<td>Start, end, and duration</td>
</tr>
<tr>
<td>Media</td>
<td>Phone, voice loop, email, face-to-face, paper, TV, computer, pager, etc.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>BME activities encoded as predicates in MacShapa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activities</td>
<td>Description</td>
</tr>
<tr>
<td>Phone</td>
<td>Telephone</td>
</tr>
<tr>
<td>VoiceLoopComm</td>
<td>Voice loop communication</td>
</tr>
<tr>
<td>FaceToFaceComm</td>
<td>In person communication</td>
</tr>
<tr>
<td>Read</td>
<td>Read</td>
</tr>
<tr>
<td>Email</td>
<td>Email</td>
</tr>
<tr>
<td>DVIS</td>
<td>Digital voice communication system</td>
</tr>
<tr>
<td>SearchComputer</td>
<td>Search computer</td>
</tr>
<tr>
<td>SearchEnv</td>
<td>Search environment</td>
</tr>
<tr>
<td>Type</td>
<td>Type on a keyboard</td>
</tr>
<tr>
<td>Write</td>
<td>Write</td>
</tr>
<tr>
<td>Monitor</td>
<td>Monitor computer, TV, or equipment screens</td>
</tr>
<tr>
<td>TimeLine</td>
<td>Calendar of events aboard ISS</td>
</tr>
</tbody>
</table>
Some of the interviews were follow-ups for gathering additional information to help clarify the live observational data. Other interviews were conducted to clarify communication, information and workflow processes of the Console BMEs. Information collected by these various methods was used for conducting functional, user and task analyses. In addition, this information was validated against the results from a distributed user and task analysis of this domain conducted by one of the researchers earlier in the study [20].

Examining the data from multiple sources and applying the HCDID methodology to the collection of data provided the researchers with insight into the complex interactions, processes, and knowledge structures between humans and artificial agents in a complex distributed environment. A detailed description of these insights will be discussed in the following results section.

3.2.2. Results of data analysis

Application of the HCDID methodology during the data collection and analysis phase uncovered many complex, interdependent, social, cultural, organizational, and cognitive characteristics of the Console BMEs’ environment. Results from the live observation and subsequent analysis revealed several key findings. During the 2-h observation, the Console BMEs worked through multiple issues with various priority levels. The characteristics of all of the issues primarily centered on the organizational memory and knowledge management issues of information exchange and communication flow and specifically, formal and informal knowledge across and with distributed groups. One issue with six sub-issues, whose properties were representative of the majority of the organizational memory and knowledge management issues identified, is chosen for discussion. The main characteristics of these sub-issues are:

1. Console BMEs thought that a similar problem had previously occurred but they were uncertain about the nature of the problem.
2. Minimal attempts by the Console BMEs to search intranet documents for information.
3. Search of hard copy manuals did not produce desired results and retrieval of information was labor intensive.
4. Time that the Console BMEs allotted to this retrieval task was contingent upon the priority of the request and whether the Console BME(s) were operating in a routine or emergency mode.
5. Problem solving was dependent upon receiving and relaying information between and across BME, Flight Surgeon, and other related domains.
6. Requests for standard, routine information resulted in numerous phone call/voice loop interactions with the Console BMEs that then generated additional activities for the Console BMEs.
7. Console BMEs encountered numerous phone or voice loop interruptions that caused the Console BMEs not to return to the original activity the majority of the time.

This observation confirmed the highly interruptive, multi-tasking work environment of the Console BMEs. The nature of these observational findings is further supported in the communication flow and information exchange results obtained from the review of the ISS Log Notes described in the following paragraph.

Review of the ISS Log Notes obtained four days prior and three days after the observation provided the communication flow and information exchange information which aided the researchers’ understanding of this complex, distributed environment. For purposes of discussion, excerpts from the ISS Log Notes addressing two of the six sub-issues identified and their corresponding communication flow and information exchange diagrams are shown in Figs. 3 and 4, respectively.

Information obtained from the ISS Log Notes revealed that during a 7-h period to resolve sub-issue #1, the Console BMEs had 10 interactions of either providing or requesting information to five separate departments associated with the Console BME domain.

Information obtained from the same ISS Log Notes revealed that during a 24-h period, the Console BMEs interacted with 12 different departments and had a total of 21 phone call/voice loop interactions regarding sub-issue #2.

Application of the HCDID methodology to the collection of data produced information that provided the researchers with a system-level understanding of the dynamic social, cultural, and organizational interactions and the cognitive processes which occur within, among and across the Console BMEs’ domain. This understanding of the context, as well as a clearly documented task and knowledge representation, provided the foundation to begin the design process of the distributed information system prototype by generating the systems requirements.

3.3. Phase 2: Systems requirements

This section describes the process of how the information obtained from the data analysis was applied to the design of the human-centered distributed information system. This includes a description of the process from the data analysis to the organizational memory and knowledge management issue identification, and then to the generation of the systems requirements.

Results from the various distributed cognitive analyses conducted in Phase 1 exposed many organizational memory and knowledge management issues. These organizational memory and knowledge management
issues were classified into four categories: organizational memory, team problem solving, communication, and work environment (see Table 2). Well established organizational memory and knowledge management terms were used to develop the classification categories [23,30–32] (Table 3).

Analysis revealed three prevalent organizational memory issues throughout the Console BMEs’ environment: (1) informal knowledge (tacit knowledge such as beliefs, perspectives and values, ideas, assumptions, meanings, questions, decisions, and stories) was not adequately captured and available for problem solving, (2) formal knowledge (explicit knowledge articulated through language and conveyed as information in books, procedure manuals, documents, databases, etc.) was available in the form of hard copy manuals and online documents, however, it was not framed in context for efficient problem solving, and (3) searching and retrieving the formal knowledge for problem solving was cumbersome, often unsuccessful and frustrating to the Console BME. These organizational memory issues impacted the Console BMEs’ problem solving abilities, their communication patterns and the nature of their work environment. For example, during the observation of shift handover, the Console BMEs were frequently asked to either provide information to or obtain information from various personnel within and across the Console BME domain. While the ISS Log Notes contained some informal knowledge and the hard copy manuals and word documents available on the intranet stored the formal knowledge, the task of searching this information was tedious and often unsuccessful. Although the Console BMEs were aware that a similar issue had previously occurred, the lack of adequately captured informal knowledge and the inability to search and retrieve formal knowledge resulted in repeated problem solving for the Console BMEs.

While the Console BMEs attempted to work through multiple issues, they were frequently interrupted by either the telephone or the voice loop and they often did not return to the original activity. These issues were sometimes complex in nature and often had multiple sub-issues nested within them. To further complicate the problem solving process, information to solve these issues was dependent upon receiving “pieces” of information from multiple sources. For example, the Console BME was asked to provide specifications on a particular instrument located on the International Space Station that is routinely scheduled for a monthly procedure. This required the Console BME to contact via telephone another department to obtain the information and then
relay that information to another department. Several hours passed and additional requests from the Console BME occurred before the Console BME was able to obtain and relay this information. Attempts to gather or provide information to resolve these issues resulted in a communication flow pattern characterized by the

<table>
<thead>
<tr>
<th>TIME</th>
<th>ISS LOG NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>04:37 BME received a call requesting routine information about equipment specifications</td>
</tr>
<tr>
<td></td>
<td>BME provided requested information</td>
</tr>
<tr>
<td></td>
<td>BME informed that they must coordinate with another department to confirm this information</td>
</tr>
<tr>
<td>08:30</td>
<td>BME called and told where to look to confirm information</td>
</tr>
<tr>
<td></td>
<td>Caller also requested routine information</td>
</tr>
<tr>
<td></td>
<td>BME provided requested information</td>
</tr>
<tr>
<td></td>
<td>BME told that another department will confirm information and get back to BME</td>
</tr>
<tr>
<td>09:36</td>
<td>BME receives call that there is a problem in executing the initial information</td>
</tr>
<tr>
<td></td>
<td>BME to relay information to another department in the morning</td>
</tr>
<tr>
<td>10:27</td>
<td>BME called and informed that initial information request is not possible</td>
</tr>
<tr>
<td></td>
<td>BME states uncertainty of who is responsible for this decision but will pursue at later time</td>
</tr>
<tr>
<td>10:10</td>
<td>BME called another department to update on this issue</td>
</tr>
<tr>
<td>10:27</td>
<td>BME received call asking for different routine information involving same equipment specifications requested earlier in shift</td>
</tr>
<tr>
<td></td>
<td>BME states that they will need to find information and return call later</td>
</tr>
<tr>
<td>13:20</td>
<td>BME contacts another department to work out issue; informed that this person will contact another department and get to BME later</td>
</tr>
<tr>
<td>15:27</td>
<td>BME called by another department asking for update on this issue</td>
</tr>
<tr>
<td>16:08</td>
<td>BME relaying updated information to 2 other departments</td>
</tr>
<tr>
<td>21:35</td>
<td>BME called and asked if confirming information was ever received</td>
</tr>
<tr>
<td></td>
<td>BME responds “no” and will try to retrieve information</td>
</tr>
<tr>
<td>Day 2</td>
<td>07:34 BME has discussion with another department about issue and possible solutions</td>
</tr>
<tr>
<td>09:03</td>
<td>BME is engaged in a conversation with another department about resolving this issue</td>
</tr>
<tr>
<td>16:16</td>
<td>BME called by another department requested update and decision on handling this issue</td>
</tr>
</tbody>
</table>

Fig. 4. Sub issue 2: ISS Log Notes excerpts, communication flow, and information exchange diagrams representing the console BMEs interactions with 12 different departments with a total of 21 phone call/voice loop interactions regarding sub-issue #2.

<table>
<thead>
<tr>
<th>Organizational memory</th>
<th>Team problem solving</th>
<th>Communication</th>
<th>Work environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Informal knowledge not adequately captured</td>
<td>Interaction and exchange of information across multiple agents distributed across time and space dimensions</td>
<td>Information relayed across various media</td>
<td>Numerous interactions requiring a high-level of multitasking</td>
</tr>
<tr>
<td>Formal knowledge not framed within context</td>
<td>Contingent upon receiving information from multiple sources Multiple sub-issues nested within a main issue Repeated problem solving for routine tasks</td>
<td>Minimal information sharing with a significant number of the group uniformed</td>
<td>Highly interruption-oriented work environment</td>
</tr>
<tr>
<td>Limited successful searchability of information</td>
<td></td>
<td>Most frequent communication pattern is one-to-one to a large distributed group</td>
<td></td>
</tr>
</tbody>
</table>
Console BMEs usually relaying information one-to-one to numerous personnel distributed across the BME domain with a significant number of the group remaining uninformed. These findings are consistent with the results of a previous related study that identified similar communication and interruption patterns \[33\].

These organizational memory and knowledge management issues provided the basis for generating the necessary systems requirements:

- Provide a means for collaborative communication.
- Capture informal knowledge.
- Organize knowledge as searchable data.
- Frame formal knowledge within context.
- Increase search and retrieval capabilities.
- Increase information sharing across groups.
- Minimize repeated problem solving with routine tasks.
- Decrease interruptions.
- Redirect one-to-one to group communication patterns.

Each systems requirement addressed one or more of the organizational memory and knowledge management issues identified.

### 3.4. Phase 3: Specifications

In Phase 3, these systems requirements were then mapped to provide the specifications necessary for the design of the information system mockup and subsequent prototype design (see Table 4). A web-based groupware from a previous NASA Johnson Space Center effort to design a collaborative problem solving workspace was used as the foundation for the new workspace mockup.

While the basic structure and function of the BME console may be described as a distributed and collaborative environment, the stressful, highly interruptive, event driven nature of this environment does not foster a user friendly, efficient means to capture, distribute, and retrieve critical information for group problem solving. Data from the various distributed cognitive analyses identified the need to create an accessible and usable, collaborative, asynchronous, spatially distributed workspace to capture both formal and informal organizational knowledge.

Design of the distributed information system mockup and prototype necessitated that all of the systems requirements be incorporated and represented as described in the specifications. During this phase, extensive

<table>
<thead>
<tr>
<th>Data analysis results</th>
<th>Organizational memory and knowledge management issues</th>
<th>Systems requirements</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thought similar problem had previously occurred: uncertain about the nature of the problem, and who, how or if the problem was resolved</td>
<td>Informal knowledge not adequately captured</td>
<td>Provide a means for collaborative communication</td>
<td>Issue specific workspace to collect items related to an issue which is accessible in one place to multiple agents</td>
</tr>
<tr>
<td>Minimal attempts to search intranet documents for information</td>
<td>Formal knowledge not framed within context</td>
<td>Capture informal knowledge</td>
<td>Workspaces that hold files, links, actions permanently</td>
</tr>
<tr>
<td>Search of hard copy manuals did not produce expected results</td>
<td>Limited successful searchability of information</td>
<td>Organize knowledge as searchable data</td>
<td>Group access at different security levels to files, links, etc.</td>
</tr>
<tr>
<td>Retrieval of information was labor intensive, contingent current BME alert mode</td>
<td>Interaction and exchange of information occurs across multiple agents, multiple mediums distributed across time and space dimensions</td>
<td>Frame formal knowledge within context</td>
<td>Asynchronous communication to decrease interruptions/increase collaboration</td>
</tr>
<tr>
<td>Problem solving was dependent upon receiving and relaying information between and across FS and other domains</td>
<td>Problem solving contingent upon receiving information from multiple sources</td>
<td>Increase search and retrieval capabilities</td>
<td>Navigation that puts users in reasonable places after completing item</td>
</tr>
<tr>
<td>Requests for standard, routine information resulted in numerous phone call/voice loop interactions over a 24 h period</td>
<td>Multiple sub-issues nested within a main issue</td>
<td>Increase information sharing across groups</td>
<td>Keep navigation to a minimum of clicks</td>
</tr>
<tr>
<td>Phone or voice loop interruptions caused BMEs not to return to the original activity the majority of the time</td>
<td>Repeated problem solving for routine tasks</td>
<td>Minimize repeated problem solving with routine tasks</td>
<td>Create fields with drop-down menus or other terminologically sound methods for entering data</td>
</tr>
<tr>
<td></td>
<td>Minimal information sharing with significant number of group uniformed</td>
<td>Decrease interruptions</td>
<td>Data organized into logical structures (concept map)</td>
</tr>
<tr>
<td></td>
<td>One-to-one to large distributed group communication pattern</td>
<td>Redirect one-to-one to group communication patterns</td>
<td>Search capability that allows specific search criteria</td>
</tr>
<tr>
<td></td>
<td>Numerous interactions requiring a high-level of multitasking</td>
<td></td>
<td>Status and task logs to capture running “at a glance” information as well as more informal information</td>
</tr>
<tr>
<td></td>
<td>Highly interruption-oriented work environment</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
representation analysis was conducted to elucidate the most efficient representations for the specifications and their subsequent tasks.

The application of the HCDID methodology highlighted the complex interdependencies between human and artificial agents that occur within the Console BMEs’ distributed, collaborative environment. The identification of these issues was the unique contribution of distributed cognition principles and the HCDID methodology. Identification of these issues permitted the researchers to then state the systems requirements and specifications necessary for the distributed information system prototype. This analytic methodology allowed the researchers to understand and describe this environment at the system level rather than at the individual level.

3.5. Phase 4: Prototype

In this final phase, a working prototype was developed from the mockups developed in Phase 3. Examples of different versions of the web-based prototype are shown in Figs. 5 and 6.

The prototype underwent evaluation, and more iteration around the Project Design Lifecycle. Fig. 6 shows a refined version of the prototype after such iterations. Extensive representational analysis was performed on the systems properties that were identified through the functional and task analysis. This process helped to guide which representation was suited for each task, to identify the most appropriate informational display requirements and to help generate the user interface. Domain-specific scenarios were then developed, volunteers were selected from the BME domain, and usability testing was conducted to evaluate the prototype design.

Information obtained from multiple sources and the analyses performed within the HCDID methodology contributed to the design of a collaborative workspace that resulted in a reorganization of the Console BMEs’ domain information structure and flow. We have been evaluating the prototype in terms of improved performance, reduced errors, and shortened learning curves. The initial results from surveys and interviews, which are two of the several evaluation methods, showed substantial improvement over the original system. While additional research on the impact of this collaborative workspace is being carried out, the HCDID methodology allowed the researchers to uncover phenomena that might not have been seen with traditional HCI methodologies.

The end result from the process of applying the HCDID methodology was the generation of the products necessary for the systems requirements and specifications of a human-centered distributed information system to address the organizational memory and knowledge management needs of the complex, social distributed environment of the Console BME domain.

4. Discussion

Designing complex, distributed information systems requires an in-depth understanding of: (1) the technological knowledge of how to build an information system, and (2) the social, cultural, organizational, and cognitive aspects that occur not only within an individual or group of individuals but also occur across
individuals and artificial agents. Traditional engineering and technology principles provide a sound, technical basis for understanding the fundamental process of information management and retrieval. However, the social, cultural, organizational, and cognitive aspects are usually omitted from consideration. Ignoring these components frequently leads to products that have sound technology and engineering but are not well integrated into the workflow. The HCDID methodology directs users to consider not only the cognitive but also the social, organizational, and cultural processes. Although this awareness is embedded throughout all phases of the Project Design Lifecycle, it is more prevalent during the data collection and analysis phase while conducting user observations, document reviews, and interviews.

In this study, we used a case study to present how to use a human-centered design methodology to design a human-centered product. This methodology incorporated the HCDID framework and the Project Design Lifecycle. The HCDID methodology was used to analyze a complex, distributed human-centered information system, to identify its problems, and to generate design requirements and specifications of a replacement distributed information system prototype for effective organizational memory and knowledge management. The user, task, and functional analysis components of the HCDID methodology allowed us to analyze the phenomena of organizational memory and uncover not only the cognitive processes but the social, cultural, and organizational process that occur within the BME domain. Integrated with the Project Design Lifecycle, which is inherently iterative in nature, the theory and methods of HCDID helped to refine the products generated from each Project Design Lifecycle phase. The concentration on the functional analysis allowed us to focus on the abstract nature of the Console BME domain and to better understand how the work was carried out and to identify what the users do.

By examining data from multiple sources obtained from a complex, distributed work environment and a methodology grounded in the principles of distributed cognition, we were able to obtain an understanding of the Console BME domain and revealed several organizational memory and knowledge management issues. The following are a few points that are worth discussion.

4.1. Public sharing of memory

In a knowledge-rich domain, public sharing of information by group members is important for the timely and accurate retrieval of the information. If the information is only in a member’s private memory, the information is not available to other members and it may not even be retrievable by the information bearer. Review of the ISS Log Notes one week prior to the observation provided useful insight about the memory sharing issue. The BMEs who had been on console during the previous week before the observation were involved in interac-
tions that were partially related to the events that occurred during the observation. However, it appeared that the Console BMEs did not recall or use this information for problem solving during the 2-h observation period. Review of the log notes and interviews with the Console BMEs and other personnel involved with the BME discipline gave us the ability to best understand this domain at a system level. Observation alone would have provided the researchers with only event-specific information. Gathering and analyzing the data using the human-centered distributed information design methodology allowed the researchers to isolate pieces of the problem and to address each issue individually. It also leads to a better understanding of why minor breakdowns in the communications and interactions resulted in significant consequences.

4.2. Informal organizational memory

The HCDID methodology allowed for the identification and close examination of how interactions across humans and artificial agents were coordinated and which artifacts were used for each interaction. Over the years, informal lines of communication developed and the Console BMEs assumed the role of “information broker.” This is due primarily because the formal knowledge housed in large, unsearchable databases was not user-friendly, either to the Console BME domain personnel or to the other supporting department personnel, and the documentation of informal knowledge was practically non-existent. Given the difficulty of using these resources, informal lines of communications subsequently developed. However, this only contributed to the intensity of the already interruption-laden, task driven environment of the BME console. As shown in Figs. 3 and 4, when the Console BME relayed information, it was usually in a pattern of one-to-one communication to a large distributed group with Console BME often providing the same information to different personnel who were involved in resolving an issue and who were distributed across space. The systematic approach of the HCDID methodology uncovered these informal lines of communications and its impact on the information flow and the Console BMEs’ work environment.

4.3. Interruptions

Closely linked to the uncovering of the informal lines of communications were the numerous interruptions incurred by the Console BMEs that were noted during the 2-h video observation. In a separate study we developed the Action Coding System (ACS), which is a language for the description, representation, categorization, and analysis of interruptions at the level of activities. We then applied the ACS to the same observational data and found that during the 2-h handover period, the Console BMEs were interrupted a total of 32 times. Most interruptions occurred through the telephone or the voice loop. The Console BME’s failed to return to task 16% of the time. It was also found that 28% of the interruptions were non-work related [34]. This insight supports the perception that the Console BME position requires multi-tasking skills to be performed in a highly interruptive, sometimes life-dependent, dynamic, event driven environment. This is further compounded by the fact that a significant portion of the Console BMEs’ attention is diverted to passive listening on the voice loop system. Observations of this interruption-laden domain highlights the need for further research to uncover the nature of the interruptions, its impact and ways to minimize interruptions that do not contribute to the functioning of the domain. A preliminary analysis of the interrupting tasks in this domain indicated that 19% could be potentially eliminated completely by information redesign, 47% could be potentially delegated to autonomous agents or automated, and 34% have to be handled by the Console BMEs but could be potentially assisted by intelligent tools or information repositories [34]. These findings could then be applied to other complex, interruption-laden domains such as healthcare to study the effects of interruptions and explore potential solutions.

Here, the HCDID methodology guided the researchers in identifying the features of the Console BMEs’ activities that are relevant for the efficiency of task performances.

4.4. System level approach

Distributed cognition principles and HCDID methodology provide a unique language to capture and describe the cognitive phenomenon distributed between and across human and artificial agents. The Console BME domain and its information systems may be described as a highly complex, asynchronous environment distributed across several time and space dimensions. The HCDID methodology was particularly useful in capturing the social cognitive nature of the Console BME domain. The individuals in this domain each possess different types of knowledge and routinely engage in problem-solving collaboration, necessitating the pooling and sharing of information across various media.

5. Conclusions

This study demonstrated how the HCDID methodology, when integrated with the Project Design Lifecycle: (1) helps provide a richer understanding of human–computer interactions, (2) enable researchers to capture the phenomenon that emerges in complex, social interactions as well as the interactions between people and structures in their environment, and (3) provide design-
ers with a process of designing human-centered information systems.

A distributed human–computer information system such as the BME console has unique properties, structures, and processes that are best described in the language of distributed cognition. These properties, structures, and processes determine the performance level of the distributed system. The HCDID methodology guides the design of these properties, structures, and processes to maximize the performance level of the distributed system.

Acknowledgments

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