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Improving collaborative work and project management in a nuclear power plant design team: A human-centered design approach

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ABSTRACT

This article presents a collaborative system, called SCORE, useful for a multi-disciplinary team designing a new nuclear power plant (NPP). It was developed during the first phase of the I^2S-LWR project (Integral Inherently Safe Light Water Reactor). SCORE enables the generation of design cards (DCs). A DC includes four main spaces (Boy, 2005): (1) a rationalization space where the various components of the system being designed (SBD) are described in terms of design rationale, integration and requirements; this space includes declarative and procedural descriptions and statements; (2) an activity space where the current version of the SBD is displayed; it includes static and dynamic features; this space enables SBD manipulation; (3) a structure space where the various components and their inter-relations are formally and declaratively described as systems of systems; (4) a function space where the various functions of the SBD are described in terms of procedural knowledge and dynamic processes involved; this space includes qualitative and quantitative physical and cognitive models. The rationalization space is informed using an adapted version of the QOC method (Questions, Options, Criteria), which was tested within the I^2S-LWR design team. The activity space contains 3D models developed using AutoDesk Inventor, and transferred into the Unity game engine web player in order to facilitate integration within the DC spaces and enable intuitive manipulation of objects in the activity space. Two additional spaces were added: an instant messaging capability that allows design team members (DTMs) to exchange with one another on a DC; and a structured evaluation space. DCs are cooperatively created and refined by DTMs, and synthesized during periodic design meetings, the frequency of which may vary. Incrementally combining abstract explanations of designed elements and integration with their explicit visual representation improves mutual understanding among DTMs, and consolidates design decisions. This human-centered design (HCD) approach also improves individual and collective familiarization with the complexity of mixing several expert contributions in NPP design. In this case, HCD is not focused on end-users, but rather on the designers themselves.

1. Introduction

Human factors and ergonomics (HFE) methods have been extensively used for the evaluation of systems already developed. In contrast, this article presents a human-centered design approach (HCD) that takes into account designers' human factors during the design process. The approach is then called HCD for designers. Designers need to collaborate to elicit, assemble and integrate complex design concepts as well as workable objects. They usually manipulate and articulate interrelated abstract concepts and concrete systems, which they need to visualize. In other words, designers need to incrementally conceptualize systems being designed.

This work started during the first design phase of the I^2S-LWR project (Integral Inherently Safe Light Water Reactor). We quickly became aware of some human factors issues emerging from a design team of 35 people having different backgrounds. Project management is not simply a matter of designing and using a linear

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Gantt chart, where tasks are well assigned. In creative projects, such as I^2S-LWR, things are more non-linear. Ideas and viewpoints need to be incrementally synthesized and integrated. There are intertwined periods of creativity and phases of rationalization. Software engineering already practices agile development. The collaborative approach that we propose in this article is strongly based on agile systems engineering. Essentially, "agile" means that at each step during the design process, punctuated by a design review meeting, a version of the product is established and is the starting point of a new step.

Design team members (DTMs) collaborating through various kinds of media need to understand each other. This is why it is required to have a common frame of reference (CFR) (i.e., a kind of music theory and overall score prescribing the symphony). This CFR is incrementally developed. CFR is also a product in itself. This article describes a CFR support system that we have called SCORE. SCORE is a mediating tool that enables design team members to generate, modify, refine and validate both physical and figurative tangibility of the complex system being designed (e.g., the I^2S-LWR nuclear reactor).

Collaborative work has been extensively studied and supported in the computer supported cooperative work (CSCW) community. CSCW is used to address "research into experimental systems and into the nature of workplaces and organizations" (Grudin, 1994a,b). Computing is used to mediate human–human interaction. Team members may interact with one another at a same or different time, and in a same or different location. There are then four cases that can be supported, combining time and space. CSCW focuses on meeting environments (e.g., interactive walls and tables, and more generally visualization systems), written and video media systems (e.g., Skype), social media systems (e.g., Facebook) and knowledge management systems (e.g., Cmaps). Our goal was to combine these CSCW capabilities for the sake of the design of a nuclear power plant (NPP), such as I^2S-LWR.

Visualization of concrete physical objects is an important part of collaboration support to share situation awareness (i.e., design team members should understand the same things). It is therefore crucial to better understand and integrate appropriate modeling and simulation (M&S) tools into CSCW means. Commercial M&S software, such as CATIA or Inventor, can be used to generate useful sources for populating the collaborative tool being currently designed. Gaming engines, such as Unity, can support dynamic and interactive attributes. Combining these tools contributes to sharing meaning among design team members (i.e., shared situation awareness).

Design is also about abstract things that need to be represented, shared and used. The field of knowledge management (KM) has already produced tools and methods to this end (Tuomi, 1999). KM is an important part of human-centered design, and more specifically participatory design (Muller, 2003). It enables design rationale capture and provides design team members with design history traceability at any time. A design team is usually a (relatively small) group of experts, from various backgrounds. They work in close cooperation, but not necessarily in the same location. They fulfill different roles, and strongly need to continuously communicate. A leader often coordinates the work of the design team. A design team is usually supported by technologies such as instant messaging; virtual team workspaces where information is managed (e.g., Dropbox); video conferencing; data conferencing; shared calendars; and discussions through a web browser (e.g., Skype, Google Hangout, VSee).

In this article, we present a collaborative tool, called SCORE, which enables a design team to create, refine and share design knowledge while designing a life-critical system such as a NPP. This tool acknowledges and supports the articulation of the duality between physical components and related abstract concepts that improve perception, comprehension and projection of the complex system being designed. Since systems are now designed as pieces of software from the beginning, using modeling and simulation tools, their functions can be tested very early during the design process. One of the main issues is their tangibility. The notion of tangibility is at the center of this human-centered design approach. Tangibility is taken in the physical sense (i.e., a physical object is graspable, and then tangible) and the figurative sense (i.e., a abstract concept is credible, and then tangible). It helps design team members to incrementally figure out and better understand components, interconnections and the whole concept of the system being designed. Therefore, collaborative HCD supports the design of tangible interactive systems (TISs), where structures and functions are incrementally articulated (Boy, 2016). The SFAC model (structure–function–abstract–concrete) is proposed to this end. SCORE is based on the creation and progressive refinement of design cards (DCs) that are shared by design team members. Simplified examples of the use of SCORE are given for the design of the I^2S-LWR nuclear reactor.

2. System design is also knowledge design: the rationalization space

A life-critical system (LCS), such as a nuclear power plant (NPP), has specific properties that directly impact the way knowledge management is carried out. A LCS is a system where loss of life could result from non-normal operations. A NPP is a complex system, which needs to be described as completely as possible, using most mature domain knowledge. Control and management of a LCS typically involves three main objectives and issues: safety, efficiency/effectiveness and comfort. These issues need to be addressed at three levels: technology, organization and people (see Table 1).

NPPs fall into the category of life-critical system of systems. Complexity needs to be handled at various levels in such systems. First, product complexity requires a great deal of identification and articulation of LCS's technological components. Second, since LCS design requires multiple background and competencies, design team complexity analogously requires a great deal of identification and articulation of design team member's roles, contexts of validity (of these roles), and resources (required to accomplish these roles). Third, organizational complexity needs to be taken into account, and we will propose a model to achieve this. The tool being proposed in this article helps handling these complexity issues.

2.1. Design knowledge and knowledge design

Designs are incrementally verified and validated (i.e., formative evaluations). In the end of the design and development process, certification by different authorities and certification bodies is typically carried out (i.e., summative evaluations). In order to get a system certified, one has to be able to justify the choices that were made, to prove, as much as possible, that extensive amount of theoretical and operational domain knowledge has been taken into account, and that the system will function safely in a large variety of difficult and even disastrous scenarios. Complex system design concurrently involves design of related knowledge. Typically, systems being developed have to be validated with respect to current regulatory principles and rules. However, when new systems are being designed and further developed, it is required to also develop additional regulatory principles and rules that accredited authorities need to certify. Knowledge design mirrors the design of the system that it supports. The system being designed and knowledge that supports it influence each other. Several iterations are necessary to reach acceptable maturity. Such maturity can be