Theme:

Title: **Knowledge Management for Reuse**

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Abstract: *Managing and reusing knowledge in architecture, engineering and construction firms can lead to greater competitive advantage, improved designs, and more effective management of constructed facilities. We define design knowledge reuse as the reuse of previously designed buildings, building subsystems, or building components, as well as the knowledge and expertise ingrained in these previous designs. This paper introduces the notion of* knowledge in context. *We argue that in order for knowledge to be reusable, the user should be able to see the context in which this knowledge was originally created and interact with this rich content. We call a repository of such knowledge in context the corporate memory. We describe empirical observations of designers reusing knowledge from their personal design experiences. Based on these observations, we formalize two key activities in the process of knowledge reuse:* finding *reusable items and* understanding *these items in context. We formalize six degrees of exploration that lead to understanding. We describe a prototype knowledge management system, CoMem (Corporate Memory), that supports these activities. CoMem is distinguished from the document-centric state-of-practice solutions by its approach of "overview first, zoom and filter, and then details-on-demand."*

Keywords: *Design reuse, corporate memory, human-computer interaction, knowledge management, knowledge reuse*

Introduction

The average designer, whether consciously or subconsciously, draws from a vast well of previous design experience. This can be experience acquired by the individual or by his/her mentors or professional community. We refer to this activity as *design knowledge reuse*. Specifically, we define design knowledge reuse as the reuse of previously designed artefacts or components, as well as the knowledge and expertise ingrained in these previous designs. We distinguish between two types of reuse:

1. *Internal knowledge reuse*: a designer reusing knowledge from his/her own personal experiences (internal memory). For example, a structural designer might remember that the last time she designed a floor slab for a hotel ballroom it was too thin, which resulted in vibration problems. The next time she is faced with a similar design situation, she designs the floor slab deeper.
2. *External knowledge reuse*: a designer reusing knowledge from an external knowledge repository (external memory). For example, the same structural designer might look for floor slab designs in her company's standard components database. She retrieves a floor slab design that comes with a spreadsheet for calculating the correct slab thickness. This spreadsheet takes into account the company's previous experiences with bouncy floor slabs and increases the depth beyond the minimum required by the building code.

Whereas internal knowledge reuse is effective, external knowledge reuse often fails. This failure occurs for numerous reasons, including:

- Designers do not appreciate the importance of knowledge capture because of the additional overhead required to document their process and rationale. Consequently, knowledge is often not captured.
- Even when knowledge capture does take place, it is limited to formal knowledge (e.g. documents). Contextual or informal knowledge, such as the rationale behind design decisions, or the interaction between team members on a design team, is often lost, rendering the captured knowledge not reusable, as is often the case in current industry documentation practices.
- There are no mechanisms from both the information technology and organizational viewpoints for capturing, finding, and retrieving reusable knowledge.

Empirical observations of designers at work show that internal knowledge reuse is effective since:

- The designer can quickly *find* (mentally) reusable items.
- The designer can remember the context of each item, and can therefore *understand* it and reuse more effectively.

We use these observations of *internal knowledge reuse* to improve *external knowledge reuse*.

We introduce the notion of *knowledge in context*. Knowledge in context is design knowledge as it occurs in a designer's personal memory: rich, detailed, and contextual. This context includes design evolution (from sketches and back-of-the-envelope calculations to detailed 3D CAD, analysis, and simulations), design rationale, and relationships between different perspectives within cross-disciplinary design teams. We define the *corporate memory* as a repository of knowledge in context; in other words, it is an external knowledge repository containing the corporation's past projects that attempts to emulate the characteristics of an internal memory, i.e. rich, detailed, and contextual. The corporate memory grows as the design firm works on more projects.

We view knowledge reuse as a step in the knowledge life cycle (Figure 1). Knowledge is created as designers collaborate on design projects. It is captured, indexed, and stored in an archive. At a later time, it is retrieved from the archive and reused. Finally, as knowledge is reused it is refined and becomes more valuable. In this sense, the archive system acts as a knowledge refinery. The current study focuses on the knowledge reuse phase and builds on previous work that addresses knowledge creation, capture, indexing, and archiving (Fruchter 1996, Fruchter et. al. 1998, Reiner and Fruchter 2000).

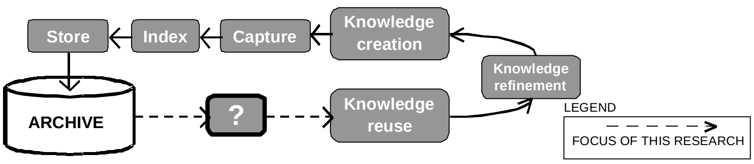

Figure 1: The knowledge life cycle

The practical motivation behind the development of external knowledge reuse systems is that the capture and reuse of knowledge is less costly than its recreation. In current practice knowledge capture and reuse are limited to dealing with paper archives. Even when the archives are digital, they are usually in the form of electronic files (documents) arranged in folders which are difficult to explore and navigate. A typical query might be, "how did we design previous cooling tower support structures in hotel building projects?" In many cases, the user of such systems is overloaded with information, but with very little context to help him/her decide if and what to reuse.

This paper addresses the following central questions:

- What are the key characteristics of the knowledge reuse process?
- How can the reuse process in the construction industry be supported by a computer system?
- What are natural idioms that can be modelled into a computer system to provide an effective knowledge reuse experience to a designer?

Our objective is to assist the designer and to support the reuse process rather than to automate it.

Related Research

Related research studies on design knowledge reuse focus either on the cognitive aspects or on the computational aspects.

Research into the cognitive aspects of reuse has helped to identify the information needed by designers. For example, Kuffner and Ullman (1990) found that mechanical engineers usually request information concerning the operation or purpose of a designed object, information that is not typically captured in standard design documents: drawings and specifications. This research extends these findings by formalizing the requirements for contextual information when reusing items from previous projects.

On the computational side, research into design knowledge reuse focuses on design knowledge *representation* and *reasoning*. Knowledge representation ranges from informal classification systems for standard components to more structured design rationale approaches (Hu et. al. 2000 gives an overview). There is a trade-off in design rationale systems between the overhead for recording design activities and the structure of the knowledge captured.

Highly structured representations of design knowledge can be used for *reasoning*. However, these approaches usually require manual pre or post processing, structuring and indexing of design knowledge. For example, ARCHIE is a case-based reasoning tool for aiding architects during conceptual design (Domeshek and Kolodner 1993). CASECAD enables designers to retrieve previous design cases based on formal specifications of new design problems (Maher 1997). Such tools enable knowledge reuse based on a priori set representations that are specific to narrowly defined domains and media types.

This research brings together the cognitive and computational approaches. We consider reuse to be a combined effort involving both the human and the computer. We therefore address the issue of design knowledge reuse as a human-computer interaction (HCI) problem, and we take a user-centred approach to designing this interaction. We aim to provide a knowledge reuse experience that leverages natural idioms and metaphors in order to support the designer in doing his/her work, and we consider automatic reasoning approaches to constrain the user's knowledge reuse activities.

In our approach, capture and indexing take place in real time, with the least possible intrusion on the design process. We take as our point of departure the Project Memory (ProMem) system (Fruchter et. al. 1998, Reiner and Fruchter 2000), which transparently captures the evolution of building design projects by supporting the typical communication and coordination activities that occur during collaborative design. ProMem is based on the Semantic Modelling Engine (SME) (Fruchter 1996), which is a framework that enables designers to map objects from a shared graphic product model to multiple semantic representations and to other shared project knowledge.

Scenario-based Design of a Corporate Memory System

CoMem (Corporate Memory) is a prototype system that extends ProMem firstly by grouping the accumulated set of project memories into a corporate memory, and secondly by supporting external knowledge reuse from this corporate memory.

In developing CoMem, we adopted a scenario-based approach to the design of human-computer interaction (Rosson and Carroll 2001). The premise behind this method is that descriptions of people using technology are essential in analysing how technology can improve or support their activities.

The scenario-based design process begins with an analysis of current practice using *problem scenarios*. These are transformed into *activity scenarios*, which are narratives of typical services that users will seek from the system. *Information scenarios* are elaborations of the activity scenarios which provide details of the information that the system will provide to the user. Interaction scenarios describe the details of user interaction and feedback. The final stage is *prototyping* and *evaluation* based on the interaction scenarios. The process as a whole from problem scenarios to prototype development is iterative.

CoMem is being developed using three sets of scenarios. In the first scenario, a novice designer uses CoMem to find and reuse a design component about which she knows very little. In the second scenario, an expert and a novice designer use CoMem together, with the expert using CoMem as a mentoring tool. Finally, in the third scenario, an expert designer uses CoMem to retrieve a design component about which she already processes a lot of contextual information, and so she uses CoMem simply as a retrieval tool.

Ongoing development of CoMem is guided by the iterative analysis, testing, and refinement of these scenarios. This paper focuses on the first scenario, that of a novice using CoMem to find and understand a component about which she knows very little.

A Design Knowledge Reuse Scenario

As part of our analysis of current practice in order to generate and analyse realistic problem scenarios, we conducted a two-week ethnographic study in a structural design office in California. The objective of the study was to investigate the reuse process qualitatively, and gain a deeper understanding of the steps involved and the types of information reused. Data was collected by videotaping, transcribing, and coding design meetings and site visits. Internal knowledge reuse was observed and recorded when a novice structural designer asked an expert designer questions. Our observations indicated that the expert always referred to his work on previous projects when answering these questions.

The following is an example of a problem scenario that was developed based on our ethnographic study.

An expert structural designer, Eric, and a novice, Nicola, both work for a structural design office in California. The office is part of the "X Inc" Structural Engineering Firm. They are working on a ten-story hotel that has a large cooling tower unit. Nicola must design the frame that will support this *cooling tower. Nicola gets stuck and asks Eric for advice. Eric recalls several other hotel projects that were designed by "X Inc". He tells Nicola to look at the drawings from the Bay Saint Louis project, a hotel project that "X Inc" designed a couple of years ago (Figure 2).*

Nicola spends over an hour looking for the Bay Saint Louis drawings in the "X Inc" paper archive. She eventually finds the drawing sheet with the Bay Saint Louis cooling tower frame. She shows it to Eric. The drawing shows the cooling tower frame as it was finally built. It is a steel frame. Eric realizes that what he had in mind for Nicola to reuse is an earlier version that had a steel part and a concrete part. He is not sure if this earlier version is documented somewhere in the archive. Rather than go through the paper archive again, Eric simply sketches the design for Nicola. Eric's sketch also shows the load path concept much more clearly than the CAD drawing would have, which helps Nicola to understand the design. Eric explains to Nicola how and why the design evolved. Given the current project they are working on, it would be more appropriate to reuse the earlier composite version. Eric recalls that the specifications of the cooling tower unit itself, which were provided by the HVAC (heating, ventilation and air conditioning) subcontractor, had a large impact on the design. Nicola now feels confident enough to design the new cooling tower frame by reusing the same concepts as the Bay Saint Louis cooling tower frame, as well as some of the standard details.

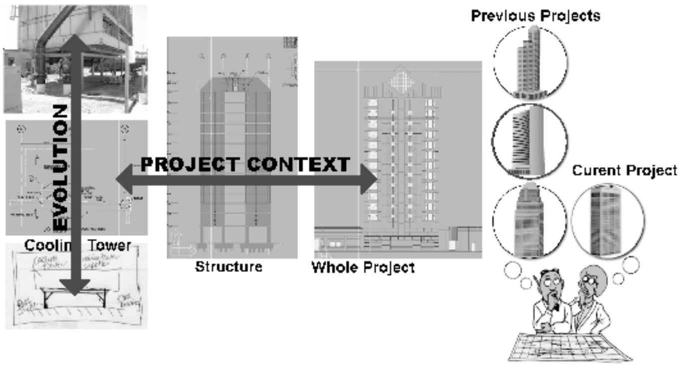

Figure 2: Reuse scenario

Using scenarios such as the one above, we observed that the expert was always able to find relevant items to reuse from his personal experiences, and he always described the project context and evolution of each item to help the novice understand it (Figure 2).

Formalized Process of Design Knowledge Reuse

During our study, the expert's internal knowledge reuse process was observed to be very effective. He was always able to recall directly related past experiences and apply them to the situation at hand. Two key observations in particular characterize the effectiveness of his internal knowledge reuse:

1. He was always able to *find* relevant designs or experiences to reuse.
2. For each specific design or part of a design he was reusing, he was able to retrieve a lot of contextual knowledge. This helped him to *understand* this design and apply it to the situation at hand. When describing contextual knowledge to the novice, the expert explored two contextual dimensions: the *project context* and the *evolution history*.

The *project context* dimension encapsulates the levels of granularity at which contextual knowledge about the design project can be explored. Given an item from the corporate memory, we identified the following directions of exploration:

- **UP: From component to subassembly**. Designers move upwards along this dimension to explore the discipline and project in which this item occurs. For example, if a structural designer considers reusing a cooling tower frame from a previous project, he/she might recall the structural system or the entire project from which this cooling tower frame is taken.
- **DOWN: From subassembly to component**. Designers move downwards along this dimension to consider the subparts or subcomponents of which this item is composed. For the cooling tower frame, the structural designer can consider the individual beams, columns, braces, and connections of which the frame is composed.
- **SIDEWAYS: From one item to related items**. Designers move sideways to explore related items in the corporate memory. For the cooling tower frame, the designer reusing the frame can consider

the cooling tower unit supported by the frame to determine what load it exerts on the frame, or he/she might explore architectural features related to the frame.

The *evolution history* is the record of how an item evolved from an abstract idea or a set of requirements to a fully designed physical entity. Given an item from the corporate memory, we identified the following directions of exploration:

- **UP: From detailed to conceptual**. Designers move upwards along this dimension to trace the concepts that were explored early on in the design of this item. For the cooling tower frame, the designer might recall a sketch of the conceptual braced frame design that was created early in the design process.
- **DOWN: From conceptual to detailed**. Designers move downwards along this dimension to follow the evolution of this item into a fully designed physical component. For the cooling tower frame, the designer reusing the frame might follow its evolution into a fully detailed design in a CAD file, and can even study photographs of the frame as built.
- **SIDEWAYS: From alternative to alternative**. Designers also move sideways to explore the different alternatives that were considered at any stage in the design process. The designer reusing the cooling tower frame might recall that steel and concrete alternatives were considered. Perhaps the concrete alternative that was originally abandoned can now be reused.

There are therefore *six degrees of exploration*, three – up, down and sideways – in each of the two contextual dimensions.

The observed process of internal knowledge reuse is formalized into three steps (Figure 2):

1. Finding a reusable item
2. Exploring its project context in order to understand it and assess its reusability
3. Exploring its evolution history in order to understand it and assess its reusability

We use these observations of *internal* knowledge reuse as the basis for supporting *external knowledge reuse from a corporate memory*.

The CoMem Approach

CoMem is designed to support the same activities observed during the expert designer's internal knowledge reuse process. The CoMem human-computer interaction experience is based on the principle of "*overview first, zoom and filter, and then details-on-demand*" (Shneiderman 1999). Based on the three reuse activities identified above – find, explore project context, explore evolution history – CoMem has three corresponding modules: an *overview, a project context explorer*, and an *evolution history explorer*.

The **overview** supports the designer in finding reusable items. The objective is to enable the designer to view the entire corporate memory at a glance. The overview gives the designer an indication of which "regions" of the corporate memory contain potentially reusable items. The overview might be extremely dense. Filtering tools are used to avert information overload and help the designer focus by adding emphasis to certain items.

Once the user has selected an item from the overview, the **project context explorer** supports the designer in exploring this item's project context. This shows the project and discipline to which this item belongs, as well as related components, disciplines and projects. The item selected from the overview becomes the focal point of the project context explorer.

Finally, in the **evolution history explorer**, the designer can explore the evolution history of any item selected from the overview. This view tells the story of how this item evolved from an abstract idea to a fully designed and detailed physical artefact or component.

CoMem Overview Module

The interaction design process for this module is based on the empirical observation that a designer can find reusable items from his/her internal memory. We argue that an external memory system (CoMem) needs to support the finding activity. We translate this activity need into an information need: the need for an overview of the corporate memory.

Assuming that the designer does not know a priori where in the corporate memory reusable items can be found, the overview should initially show all items. The overview needs to provide a succinct "at a glance" view of the entire corporate memory. CoMem uses a map metaphor for the overview. Figure 3 shows a map of the "X Inc" corporate memory from the scenario. The squarified treemap (Bruls et. al. 1999) technique is used to display an overview of the corporate memory. The corporate memory consists of multiple project objects, each project object contains multiple discipline objects, and each discipline object contains multiple component objects. In the overview projects, disciplines and individual components are represented as nested rectangles.

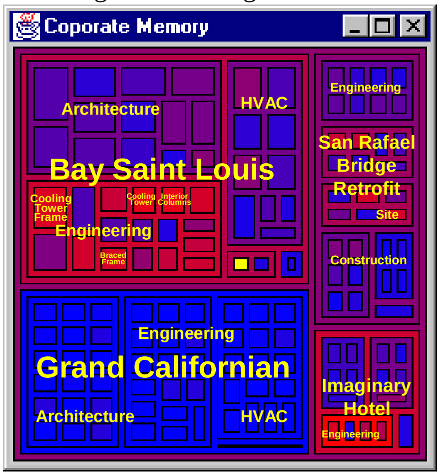

Figure 3: CoMem overview

The rectangles are laid out so as to minimize the average aspect ratio of the rectangles. The area on the map allocated to each item is based on a measure of how much knowledge this item encapsulates, i.e. how richly annotated it is, how many times it is versioned, how much external data is linked to it. Each item on the map is colour-coded by a measure of relevance to the designer's current task. Currently, this relevance measure is based on latent semantic analysis (LSI) (Landauer and Dumais 1995) of the textual data in the corporate memory.

CoMem allows the user to filter out items from the overview using dynamic querying. In a dynamic querying environment, search results are instantly updated as the user adjusts sliders or buttons to query a database (Shneiderman 1994). The designer can filter based on relevance, date, keywords, or ownership. Items that are filtered out can either appear greyed out, or are not drawn at all, leaving more space for the remaining items. For a corporate memory containing many thousands of items, these filtering tools can be used to reduce the number of items displayed in the overview.

CoMem Project Context Explorer Module

The interaction design process for this module is based on the empirical observation that a designer can understand a found reusable item because he/she can remember that item's project context. We argue that an external memory system should support project context exploration. We translate this activity need into an information need: the need for details on demand about an item's project context.

The project context explorer supports the designer in exploring the project context of any item selected from the overview. This item becomes the focal point of the interaction. CoMem uses a fisheye lens metaphor for the project context explorer. A fisheye lens balances local detail with global context. This metaphor is used here to suggest that the designer is initially concerned only with the item of interest, but begins to explore the context "outwards" as necessary.

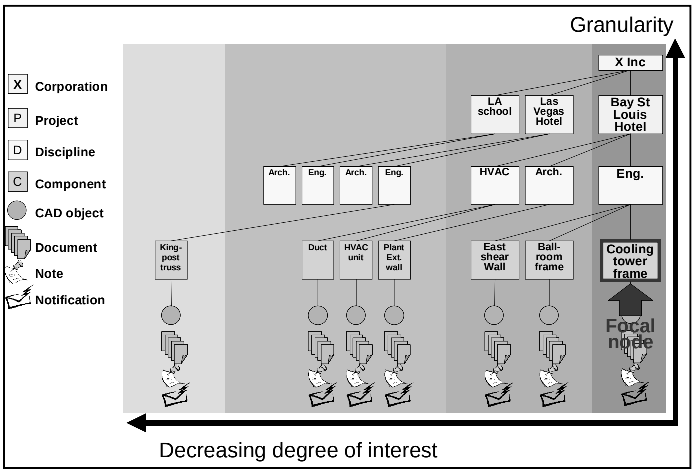

Figure 4: The CoMem project context explorer

Given a user-specified focal point, CoMem uses the fisheye formulation (Furnas 1981) to assign a degree of interest to every item in the corporate memory. Items with a higher degree of interest are displayed more prominently in the project context explorer. Figure 4 shows a view of the CoMem project context explorer. Each object is positioned in the vertical axis according to its level of granularity, and in the horizontal axis according to its degree of interest. The current focal node, in this case the Cooling Tower Frame component object, is displayed at the right hand side of the image, along with the Engineering discipline object and Bay Saint Louis project object to which it belongs. To the left of those are items that are one degree of interest down from this: other projects in the "X Inc" corporate memory, other disciplines that were involved in the Bay Saint Louis project, and other components that were part of the Engineering discipline. This visualization emphasizes structural relationships in the hierarchy that are obscured in the treemap, and facilitates effective exploration of the focal node's context.

CoMem Evolution History Explorer Module

The interaction design process for this module is based on the empirical observation that a designer can understand a found reusable item because he/she can remember that item's evolution history. We argue that an external memory system should support evolution history exploration. We translate this activity need into an information need: the need for details on demand about an item's evolution history.

The evolution history explorer enables the designer to explore the evolution history of any item selected from the overview. This view tells the story of how this item evolved from an abstract idea to a fully designed and detailed physical component, discipline subsystem, or even entire project. CoMem uses a storytelling metaphor for the evolution history explorer. This is based on our observation that the most striking means of transmitting knowledge from experts to novices in design offices is through the recounting of experiences from past projects. Stories convey great amounts of knowledge and information in relatively few words (Gershon and Page 2001).

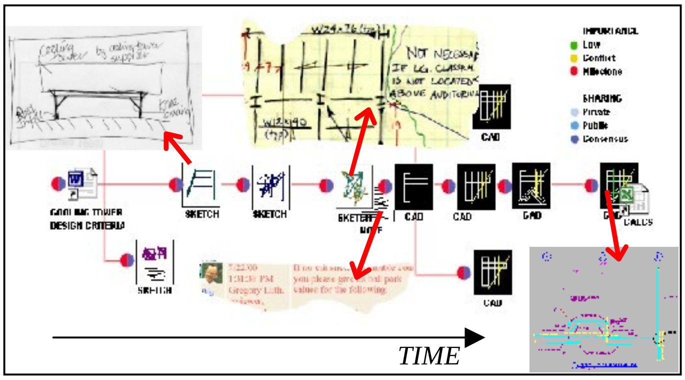

Figure 5: The CoMem evolution history explorer

In the evolution history explorer all the versions of an item captured by ProMem are displayed. Each version is represented by a circle that is colour-coded to indicate this version's level of importance (low, conflict, or milestone) and level of sharing (private, public, or consensus). The levels importance and sharing are provided by the original designers working on the project. Next to this circle, thumbnails appear for any CAD objects, sketches, documents, or notes linked to this version. The designer is able to click on any of the thumbnails for a larger view of this content (Figure 5). With all the versions shown, the display can be very dense. The designer is able to filter out versions based on the levels of importance and sharing.

Scenario revisited

Imagine that Nicola has at her disposal the CoMem prototype. After exploring the corporate memory for just twenty minutes, she should feel almost as if she has worked on each and every one of the cooling towers "X Inc" has been involved in. In particular, she will be able to locate from previous projects valuable starting points for the cooling tower she now needs to design. She can even import some CAD drawings directly into her current CAD model.

Conclusions

From empirical observations, we identify three steps in the process of internal knowledge reuse: find, explore evolution history and explore project context. We argue that a system for supporting external knowledge reuse should emulate this process. We describe CoMem, a prototype corporate memory system that supports these three activities using three modules: an overview, a project context explorer, and an evolution history explorer. CoMem proposes metaphors based on natural idioms for each of the three modules: a *map* for the *overview* module, a *fisheye lens* for the *project context explorer* module, and *storytelling* for the *evolution history explorer* module.

The map metaphor serves as an effective conduit of knowledge from the computer to the human. It provides a succinct representation that facilitates rapid and targeted knowledge finding.

The project context provides succinct and focused contextual information by using the fisheye lens metaphor to control the amount of data generated and represented. It enables the designer to understand the item whose context he/she is exploring, as well as to reformulate the reuse problem in terms of reusing a larger or smaller grain of the design, or reusing a related item based on his/her interest.

The evolution history explorer provides a rich, contextual representation of the evolution of project data, information, and knowledge over time. This facilitates better understanding of past solutions and decisions, which in turn enables the designer to decide what and how to reuse.

Preliminary observations indicate that CoMem supports effective knowledge reuse. The map enables the finding activity much faster than, for example, searching for files on a hard drive using the Microsoft Windows explorer. The project context explorer and evolution history provide contextual information that is not provided by state-of-practice systems, such as CAD file repositories or archived project extranets. This facilitates understanding of the item being reused and leads to informed and responsible reuse of design knowledge. We plan to conduct further usability tests and a formal validation of CoMem with a number of industry partners.

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