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ADAPTING AEROSPACE DESIGN RATIONALE MAPPING TO CIVIL ENGINEERING: A PRELIMINARY STUDY

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ABSTRACT

A pilot study of aerospace design rationale capture methods in civil engineering was performed to improve support for information management and systems thinking. Deploying software-based methods in complex socio-technical environments presents many challenges. Digital tools are often force-fit into work in ways that disrupt communication and understanding. This study seeks to mitigate potential disruptions through careful study of opportunities for innovative, localized variations in civil engineering. Data was collected through adaptation of existing documents into map-based formats, examination of information repositories and informal interviews with engineers exposed to the mapping methods on a live project. Results echo previous work comparing these industries, highlight current limitations of “paperless” visions and point to adapted mapping methods that better fit the civil engineering context. Future work will extend this study towards developing an effective infrastructure to support more holistic, competitive and sustainable design of the built environment.

Keywords: knowledge management, AEC, diagramming, concept mapping, CSCW

1. INTRODUCTION

Technical knowledge across the architecture, engineering and construction (AEC) industry is unstructured and traditionally poorly managed; clients, architects and engineers focus on the challenges and constraints related to their own roles and often only the obvious interfaces between disciplines are deeply discussed. The design is also influenced by market conditions, materials availability, site constraints and quality control difficulties on site. Builder performance is highly dependant on their previous experience so design decisions tend toward well-know construction methods, leaving little space for innovation. On the other hand, from a socio-economic perspective, repetition of building aesthetics is undesirable and bespoke layouts are often required to satisfy specific user requirements. As a result, the design and construction of buildings can be described as continuous prototyping based on well-established methods and materials. True innovation is rare and requires coordinated efforts from all professionals involved in the design. Motivation to invest those efforts is limited compared with the rewards available for innovation in other industries where patents and copyrights make the difference between success and survival (aerospace, electronics, product design).

Despite its traditional context, the construction industry is starting to feel the effects of the ‘digital revolution’. Most design information is produced on computers and communicated by email. Building Information Modeling (BIM) is becoming the new tool for design coordination and, in some cases, the form of design deliverables required by contractors and clients. However, BIM models generally represent only the end product of the design process (a virtual prototype). The processes that lead to a specific design solution are often owned by a limited number of individuals and this understanding is not well captured. The result is an inability to adapt or innovate because new solutions that span across disciplines cannot be explored or discussed. Detailed design decisions are made despite other disciplines, not in cooperation with them and this hobbles improvements in system performance. Overall understanding of the design process requires the set-up of a comprehensive knowledge management system able to identify, capture and disseminate information related to design decisions.

This work seeks to fill some of this gap thorough the introduction of map-based rationale capture methods that have demonstrated some success in other areas, notably aerospace engineering [1] and group facilitation [2]. This study builds on existing work that seeks to better understand what is required of mapping tools in engineering design [3]. The proposed mapping solution involves methods that clarify ideas through the layout of simple symbols, text and arrows. They represent the connections between various ideas on their own as well as existing documentation. As illustrated in Figure 1, the result is a new information layer that captures and assembles the "connected thinking" of engineers and relates it clearly to otherwise messy information.

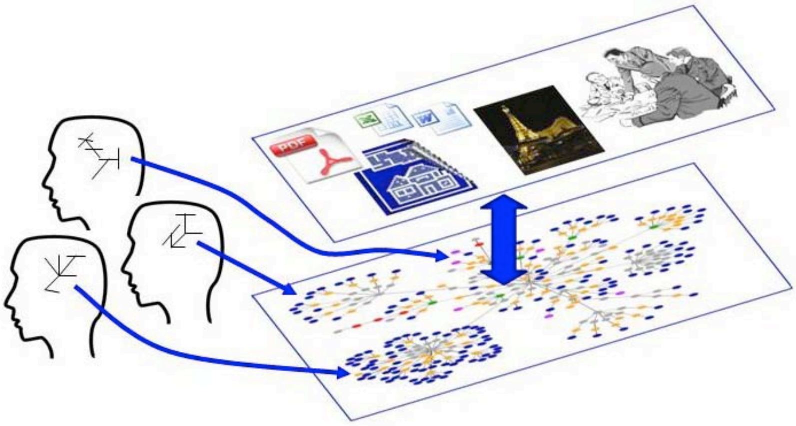

Figure 1. Capturing the Layer of Connected Thinking Across People

The idea is that creating a representation of this layer allows it to be better understood and shared. It is not about having an all-encompassing data model but about users interacting with conceptual relationships more explicitly to improve understanding. This has been found to integrate well with design work in aerospace [1] and it is hoped that it will be equally beneficial in the civil engineering context. The introduction of new tools can, itself, pose numerous difficulties. Henderson, for example, reports on the challenges created with the introduction of CAD to engineering work. Most of the problems were due to a neglect of the nature of engineering knowledge and communication [4]. It is important to ground optimism about new digital tools with situated observations that take these less tangible aspects into account.

1.1. Research Goals and Paper Outline

This research aims to support more transparent, distributed decision-making across the organisational silos in AEC. The kind of visibility and coordination afforded by knowledge maps is essential to shift traditional decision perspectives if the industry is to innovate in difficult areas such as sustainability.

A critical failing of many potentially beneficial initiatives, especially in the area of knowledge and information management is that their promises of future value are not matched with actualized, immediate value. Similarly, there are infrastructure costs, debugging and training requirements to implement new systems. It is not possible to motivate the investment in effort to capture *something* for *someone* at *some time* given the scarcity of available resources. Avoiding "reinventing the wheel" must be a bonus, not the main reason for putting in extra effort in learning or using different tools. The interventions presented here aim for an immediately valuable impact by examining typical success and advantages of mapping and then testing them in the new field.

Given the disconnectedness of AEC organizations along the building lifecycle, the authors suggest that capturing and communicating the interdependencies between stages can create new opportunities extending beyond efficiency into creativity. It is hoped that these methods for augmenting communication will enable multiple stakeholders to design richly structured collaborative innovations that are robust enough to survive the AEC lifecycle.

Finally, the aggregate result of everyday impact and creative solutions will be an improved competitiveness and environmental integration. It is these integrative skills that enable the jumps in capability required to really address organizational competitiveness and genuinely sustainable environmental practices.

The next section will review some theory behind knowledge transfer between disciplines, challenges in deploying software-based methods and the potential gains of design rationale mapping. Section three will present research methods. Section four presents the observations which are analysed and discussed in Section five. This discussion reviews specific requirements, changes in approach from aerospace and directions for future development.

2. CROSSING SECTORS AND DIGITIZING DESIGN

This section briefly reviews the context and theory surrounding this study beginning with a comparison of industries, followed by a more detailed look at the theory behind digital tools and concluding with an introduction to a key mapping method.

2.1. AEC versus Aerospace Industries

The AEC industry is of vital importance to modern society. In the UK, for example, AEC employs 1.6 million people and turns over £83.59 billion per year. In contrast, aerospace employs only around 117 thousand people and turns over £16.14 billion [5]. From an environmental perspective, nearly half of all UK energy use is related to heating the built environment [6]. From a social perspective, the built environment is what society interacts with on a daily basis. Its success creates hubs of productivity and commerce. Its failure directly harms individuals and cripples society. Despite this significance, AEC industry suffers from a number of barriers to more sustainable practice compared to aerospace. These are reviewed in Table 1.

Table 1. Contrasting AEC and Aerospace Industries

Aspect	AEC industry	Aeronautical industry
Nature of services and design ownership	Services are fragmented across forms of consultancy (from architecture to engineering) and generally separated from construction (manufacturing) and maintenance.	Owned, integrated and provided by the same firm.
Nature of the market	Low technological entry barriers make feasible for many entrepreneurs to get involved in AEC (e.g. a house is far easier to build and maintain than an airplane).	High-tech infrastructure and global competition mean companies consolidate into a few global corporations.
Size of companies and level of consolidation	AEC is configured to be an "over the wall" endeavour. However, large firms in AEC are branching out to services/studies related to the building lifecycle.	Big aerospace firms have an interest in controlling information from early research to service (e.g. Product-Service Systems)
Design constraints and technologies	Clients briefs, site constraints, planning / programme, building permits limitations, sustainability targets and budget available change from project to project: **constant prototyping**. Building materials and construction products are selected from a well-tested set of components.	With the exception of the design of completely new products, the design is generally developed starting from a basic design of previous or similar version of the same product (e.g. engine, turbine, airframe, etc.).
Design quality	Complex differences between site uses make comparison difficult. The qualities of the consultancy and construction services are not necessarily related to the quality of the end product. The latter is more led by budget and other constraints.	Quality of the design is directly measurable and comparable (e.g. performance of the engine, cost and durability). Note that 'quality of the design' affects position of a company on the market.
Innovation	Client's vision and architectural aspirations are essential to drive innovation. It does not happen easily. Design innovation does not generally lead to copyrights and patent applications.	Creativity and innovation are required to be competitive and maintain a place in the market (e.g. need to develop new and more effective technologies, ownership of patents).
Design media format	Civil engineering also has a long tradition of working through large-format drawings that are integral to interactions with clients and contractors on site.	Digital technology is broadly adopted across aerospace industry. Shared and archived documents are digital.

The differences highlighted in Table 1 outline possible obstacles in applying digital technologies, like rationale maps, to the construction industry. Fortunately the advent of new technologies, design tools and knowledge management practices in the construction industry is creating new opportunities for implementation. Large firms in AEC are branching out to cover more of the building lifecycle to close gaps in communication and find efficiencies (e.g. Building Information Management (BIM)).

2.2. Digitizing Design

Engineering work has been the focus of significant ICT development thanks to its tangible outputs and numerous formal representations. Beyond the standard email, web browser and office applications, the technical industry is awash with invaluable software systems for Computer Aided Drawing (CAD), Computer Aided Manufacturing (CAM), Product Data Management (PDM), requirements management, Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), and much more. Engineering products can now be imagined, prototyped, manufactured and distributed in ways and with efficiencies unimaginable a few decades ago.

The transition to newer, "better" digital technology is not generally a smooth one. Henderson [4] details many of the failures of early CAD deployment caused by a lack of understanding of how engineers actually work and communicate. Existing methods of working often contribute to understanding and troubleshooting in ways that are difficult to perceive through optimized, computer-oriented idealisations. This is not to say that digital tools have failed in engineering, but that their deployment must be done *appropriately*. Many informal representations, such as sketching, are now understood as inextricably linked to their *apparently* low-tech pen and paper media which, when combined with a designer's thinking, are very advanced tools [7].

Another source of difficulty is misconceptions about the nature of data and information. Information management initiatives that seek to capture all information in one place are only solving part of the problem. Tuomi, for example, notes how information always requires significant input of contextual knowledge to be put into action [8]. Creating information requires formalization which also has numerous social ramifications. It forces work to become more "visible" which affects its perceived value and the social status of those that do it [9]. Thus, the act of creating new kinds of information conscripts future workers into making sense of it and subjects it to the political effects of visibility.

A third problem with new digital media is that they are not fully understood. McLuhan notes that "…new technological environments are commonly cast in the molds of the preceding technology out of the sheer unawareness of their designers" [10]. In other words, new technologies are expected to perform the same work with the same content as the old. In AEC, the delivery of design information through BIM technologies has caused arguments and, in some cases litigation, between engineers, clients and building contractors due to the quality and expected accuracy of the content. BIM provides a break-down that only reflects what is drawn. Items that were often between disciplines or outside the scope of a single discipline must now be *explicitly* added or listed as excluded. Rationale mapping is expected to support the thinking process and automatically highlight inadequately explored directions.

2.3. Mapping Design Information

A common thread among digital tools deployed in engineering is that they have not generally addressed larger systemic issues like understanding how each result is related to others. They are "point tools", useful within their tight scope but isolated [11]. A coherent overview exists only across the human minds of the organisation. What is needed is a way to help people integrate their thinking across the various digital representations (e.g. shown in Figure 1) without being bound to too much *a priori* structure. Computer-based concept mapping tools present a potential solution [1][3][12]. A specific method called rationale mapping is presented here.

2.3.1. Example of Rationale Capture

A rationale map is one of many kinds of maps supported by the proposed software tools. This map in particular is designed to capture the reasoning behind the evolution of ideas. It is powerful because it helps users clarify their thinking while, at the same time, creating a rich record of the decision-making work. Rationale maps are based on Horst Rittel's "issue-based information system" (IBIS) for working on "wicked problems". That is, problems without clear answers, where each solution is a single-shot experiment and where the very definition of the problem is ever-shifting [2]. The mapping technique uses three types of elements: questions (issues), solutions (answers) and arguments (pro or con). In a rationale map these may be visually represented as question marks, light bulbs and '+' or '-' signs. The arrows linking concepts follow logical dependencies. This contrasts with many other maps where arrows indicate direction of reading or temporal processes. Figure 2 presents the graphical development of the example problem of "how to get home". This sort of map would be constructed roughly from left to right, as indicated by the underlying arrows.

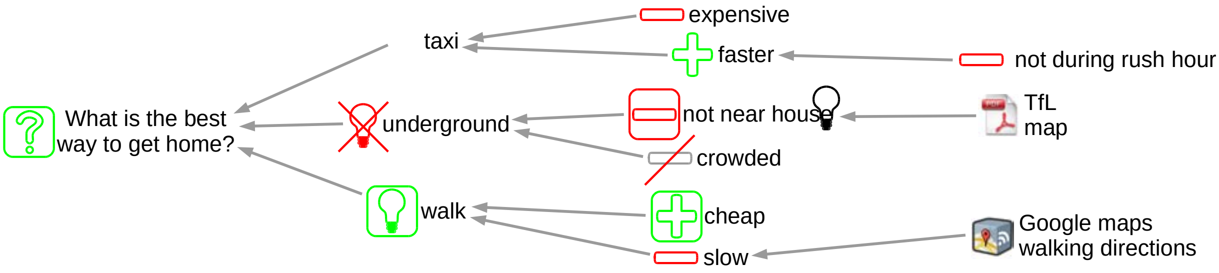

Figure 2. Mapping and Evaluating an Issue

Once a problem is laid out, the user can go back through the "tree" of options and assess the validity of its structure. In this case they would evaluate the rationale from right to left. The symbols in Figure 2 also indicate changes in *status*. For example, the "crowded" argument against using the underground was *rejected* but the fact that the underground was "not near the house" was considered a *dominant* argument (box around '-') and thus grounds for *rejecting* that answer (crossing it out). On the other hand, the fact that walking was "cheap" was enough to *accept* it over taking a taxi. The answer "walk" was *accepted* and the core issue (far left) was set as *resolved* (green box).

Note that all of the above operations are performed by the human users. There is no expectation that the computer understands the complexity of what is referred to, nor should there be. This is a form of shorthand for "sketching" ideas that aids in remembering all the related details. Its focus is ease of creation and speed of review.

In practice the progression of a dialogue can go in any direction. One might reject a question in favour of a better one because it is, for example, less leading or more specific. Answers and arguments may, themselves, raise further questions and so a pattern of question-answer or question-answer-argument "phrases" repeats itself as needed. It may appear messy initially, but consider the length of the equivalent text document required to describe all the examined options, why they were accepted or rejected and what was still in process when the issue was resolved. Recording incrementally, one idea at a time, means that if work pauses, documentation is still "complete" up to that point. This feature of map-based work overcomes some issues with incomplete retrospective reporting. IBIS "grammar" eases real-time structuring while making important aspects of the rationale visible. Overall, mapping:

- highlights "dangling answers" that serve no particular problems;
- indicates one-sidedness of arguments where only positive or negative points are presented; this is often a problem with short narrative rationales;
- documents both final conclusions and "blind alleys" so more results can be reused or reviewed;
- shows where effort could be immediately valuable if the chosen solution is incomplete or breaks.

Many of these features are particularly valuable in AEC where projects may be dropped and restarted with different people. The complexity of projects means that even if the same engineers resume a project, they may not remember why they made certain decisions.

If the number of answers or suitability of pro or con arguments has shifted, it is possible to quickly revisit decisions with equal or better consideration than the first time. Existing work is thus available for auditing or reuse. This creates a sort of resilience in decision-making that is critical in a fast-changing environment. Resilience is different from robustness in that it emphasizes a recovery after a failure instead of just the prevention of failure [13]. The result is a promising way to mitigate well-known sources of extra costs and programme delays in AEC.

In the context of design reviews, reviewers can quickly audit the depth of rationale behind key decisions and develop trust in the overall rigour of reasoning. Most important, however, is the immediate value played by the maps in helping a user to clarify their thoughts on the go. This is one of the things that motivates the initial adoption into everyday use and makes all the other gains feasible.

3. RESEARCH METHOD

Due to the simultaneous interactions involved in studying socio-technical systems, the authors chose a flexible qualitative approach to begin to build an overview of important issues. Moving from aerospace to civil engineering might provide many lessons that are too subtle to be captured with a more quantitative method like a survey. It is first necessary to determine what the important interests are and to gauge the potential level of access to engineers. The work was done at the level of a pilot study to initiate key relationships and to create realistic examples to motivate broader adoption. It is understood that this level of data affects generalisability and future work will seek more data points to support or refute these preliminary conclusions.

3.1. Design Research Framework

Design Research Methodology (DRM) can be used as a situating framework to explain how this work fits in with other research activities. This work covers elements from early Description I and Criteria setting. The following Figure, based on [14], illustrates the general area treated.

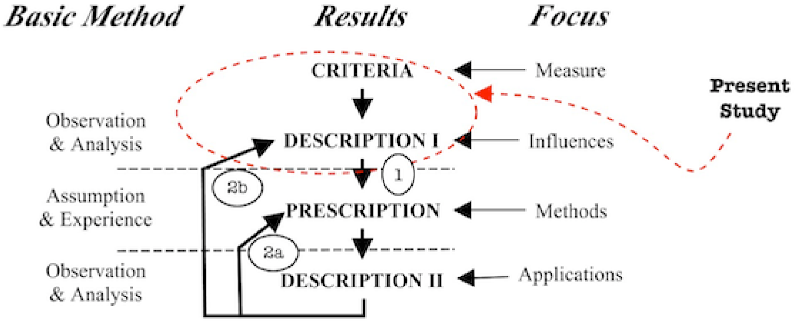

Figure 3. Situating Study within DRM

AEC industry seems to need improved methods of understanding design decisions across disciplines. The *criteria* for success is the understanding and sharing of design information which leads to more innovative design. Only initial work on the *first descriptive study* (Description I) is presented here which searches for examples where a failure to understand design information is obstructing decision making or project performance. Further descriptive work will be done in the next research step to elaborate on the opportunities found so far. It is also important to note that the link to rationale capture in aerospace embodies the rarely addressed outer *feedback link* (2b) [14]. This research builds on knowledge from a completed DRM cycle [1] which is also ongoing. Table 2 further elaborates on study characteristics in line with [14].

Table 2. Characteristics of Design Research Studied

Aspect of Studied Process	Value (notes)
Environment	International civil engineering company
Nature of Study	Exploratory
Data Collection Methods	Observation, document analysis, collected drawings, interviews
Subjects	Engineers with 3 to 30+ year's experience
Number of Cases	Two: one live project, one project in archive
Team Size	Three to six primary engineers in each project
Time Constraint	(Researcher not in position to apply time constraint)
Duration	Projects approx 18 months in duration (sampling over 4 months)
Continuation	Sampling was opportunistic and discontinuous
Role of Researcher	Non-participant observer and method consultant
Required Results	Documentation for other engineers; proposals for method implementation methods and procedures
Design Object Type	Original and Variant (building adaptation)
Topic	Building design
Batch Size	One-off (like most civil engineering projects)

3.2. Data Collection and Analysis

The pilot research work was performed opportunistically at an international medium size building engineering consultancy firm with guidance from a senior partner and a mid-level engineer who served as the "method champion" for the study. Observation, discussion and interview notes were collected in a dedicated notebook. Collected archive data included numerous example files for reverse-engineering into map form. The idea of the reverse engineering work is to create a view of a realistically complex problem that can be shown to civil engineers to better evaluate the mapping methods. The limitation to this approach is that it is retrospective and thus neglects many of the challenges in the initial creation process. Once useful maps are identified, further live experiments will be needed to assess this. Collected files mostly consisted of portable document format (PDF) scans of engineering drawings and standard office documents (word processing and spreadsheet). Researcher's early presentations also served as a record of early hypotheses.

A qualitative analysis was performed on the data by parsing statements and observations into a number of categories. Emerging conclusions were fed back to the method champion throughout the study to aid in prioritization of the next step. This provided grounded examples discussed §4 and §5.

3.3. Software Selection

Among the numerous software tools were potentially suitable for the study, the Open University's Compendium [15] was selected. It has native support for IBIS maps; It is stable and freely available, and the authors have experience with it. No single mapping system is currently ideal for engineering design support and future work may extend to other systems which enable additional visual notations such as IHMC CmapTools [16] or Tufts University's Visual Understanding Environment (VUE) [17]. More details on selection and practical issues in engineering design mapping can be found in [3].

4. OBSERVATIONS

Observations were collected over the course of several months, as project loads allowed and as senior management became available for discussions. Key observations are collected here to serve as a reference for later discussions. When the study was initiated the following key mapping applications (hereafter abbreviated to as MA) were discussed with senior management:

1. Early, unstructured information management such as brainstorm mapping and concept selection;
2. Stakeholder mapping for multidisciplinary teams;
3. Rationale capture (as described in §2.3.1) with integrated links to underlying information, possibly including BIM repositories;
4. Reusing knowledge and information relating to similar sites, buildings or client needs;
5. Requirements management;
6. Design Review meetings;

Opportunities for testing these were sought through studies of the use context, mapping on live projects and reverse-engineered information presented in this section.

4.1. Information Use Environment

The principal researcher spent a day working in the civil engineering office of the collaborating company while examining a representative project information collection. Researchers were given access to a completed project on a public building. Files were reviewed and samples collected for later reverse-engineering work to evaluate integrating mapping with the IT system (MA3 and MA4).

The project of interest consisted of 50GB of information across 60 000 files. A quick examination of similar projects suggested that this is typical and that newer projects are consuming increasing space. These numbers mean that unguided manual information searches are probably futile. There is a folder structure template across the company but it is not used consistently because of the variability of project needs and flexibility allowed by the system. Generic folder names are sometimes ambiguous so users often change them outright or give up and dump files into the "miscellaneous" folder instead. The size also implies that it is impractical to duplicate the information in too many places, especially given the number of ongoing projects. Data management systems like Microsoft Sharepoint are in place but these tend to be used for final copies, leaving out the process as captured in project folders.

In addition to challenges with the scale of information, there are numerous challenges with repetition. For example: important documentation lies in collections of weekly presentations that tend to repeat a lot of the same material each week with small variations. Trying to get a handle on those subtleties as a new project engineer is tedious at best. A large proportion of the overall project files are scanned drawings stored in PDF format. Among other things, these create an auditable *paper* trail of the state of the project in case review is required. The changes here are also often small additional sketches since it is prohibitively time consuming to fully reissue all drawings for each change.

4.2. Discussions with Engineers

Discussions and informal interviews occurred with six engineers around the company. They ranged in experience from a few years to multiple decades. In meetings we presented printouts, presentation slides and mapping software demos. Comments of interest covered a number of areas:

- Inherent challenges in civil engineering;
  - Project ownership: "Design teams have to make [reassigned projects] theirs" through an understanding of the process.
  - Unavoidable uncertainty: "You never really know everything when you start with an existing building". For example, foundations may be difficult or impossible to fully survey.
  - Fragmentation: no cross-discipline ownership and constant prototyping.
- Perceived information management problems in the organization;
  - "We fail at catch up with new owners of projects".
  - Existing documentation captures results, not processes (impeding ownership transfer).
  - BIM is not yet seen as capturing design decisions but tracking results.
  - Design review: one hour exercise that provides enough time to tell a sort of story of the work done but never with enough depth.
- Requirements for a holistic information management tools;
  - Organize work around tasks: "we think in tasks";
  - Time saving: Saving a half hour of a director's time is a lot of value (see design review);
  - Organically connected: "a thing on which you could pin a growing body of data";
  - Accessible: filter initial maps so as not to overwhelm new viewers;
  - Simplicity: "easy enough so you don't have to think about it and can focus on design";
  - Adaptive: "has to scale and be tinkerable"

After these general discussions, the "method champion" took it upon himself to put the selected software tool to work wherever possible over the next few months and to introduce it to others. His experiences are exemplified in the following "live use example" in the next section.

4.2.1. Live Use Example

A project that was suspended due to funding had just been resumed. It was the job of the method champion and his colleagues to get it back under way and complete it. The scenario resembled MA1 in terms of the need to make sense of unstructured ideas. The method champion used Compendium to lay out task-related questions that needed answers before proceeding on the project (map 1 in Figure 4).

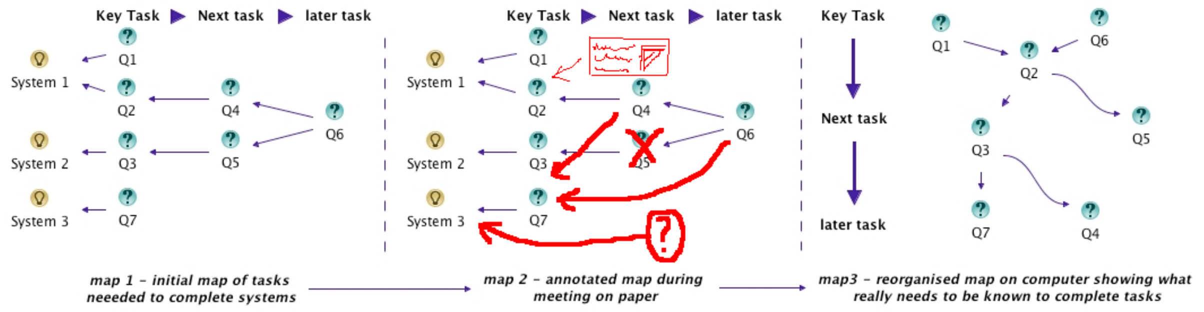

Figure 4. Live Use Example Workflow

This map is different from the typical IBIS map shown in Figure 2 as it consists only of issues nodes. The champion decided to use the map to discuss open issues. Instead of relying on the limited map space available on his laptop, he brought a colour A3-sized printout to the meeting. He did not introduce the tool or its symbol system but began the discussion around the map. Unfortunately a number of factors led to poor initial reception. There was elevated stress created by approaching project deadlines, colleagues on leave for the next few weeks and counterintuitive map conventions. In a subsequent interview with the researcher, one of the meeting participants noted that his initial "feel" for the maps resembled that of the often mocked power point slide on the US strategy in Afghanistan:

a mess of spaghetti and words. He noted that some sort of visual filter "would have been nice" for the novice map user. It was also difficult to read since issues were used to represent tasks and the convention for arrow directions in IBIS is the opposite of that used in more familiar flowcharts. Instead of protesting, however, this participant used a common point of reference for navigation: headings that matched his assigned tasks. The meeting proceeded with pen-based annotation of the map. The champion later re-formatted the map to a pseudo-table (map 3 in Figure 4).

4.3. Reverse-engineered Information

This evaluation looked at the feasibility of MA3 by attempting to capture or link existing files with maps in a useful way. The first document to be reverse-engineered into a map was a large spreadsheet. It consisted of a dozen sheets which each represented standard AEC project stages. Each of these sheets, in turn, detailed the information civil engineers needed to provide to other disciplines to complete the stage. These tables were relatively sparse since not all actors needed inputs at all stages and information was repeated in several places. Using the inter-map linking capabilities of Compendium, these repetitions were eliminated and new views were created that integrated perspectives on related data. Unfortunately these were not found to be useful in later reviews. The tables were just densely populated enough that arrows and text boxes were overly cluttered. Further work might involve refining a table-map hybrid view for this sort of information.

The second document modification was an attempt to mesh together a coherent map set around the collected files from the archive study. Rationale maps were drawn directly on top of engineering drawings using image import functions in Compendium. These could then be clicked on to access related information. Instead of having to deal with the inconsistent folder structure, key drawings themselves were turned into information retrieval tools that link to technical details or key rationales.

A last point of note is that a significant bug was encountered in the software during this test. Fortunately, the main developer of the open source tool was immediately available and the problem was solved through a reportedly difficult debugging process. The experience served as a gentle reminder that even if a tool is "free" it is essential to invest in securing reliable support.

5. DISCUSSION

The discussion brings together the threads presented, beginning with what has been found to work, followed by directions for the next phase. The results discussed are summarised in Table 3.

Table 3. Summary of Methods Evaluated in Civil Engineering Context

Mapping Applications (MA)	Initial Result	Additional Notes
(1) Sense-making in early unstructured design work and brainstorm concept selection (§ 4.2.1)	useful	Rigorous brainstorming is a particular tool that was not observed but the general flexibility of maps to help organise unstructured information came through in the live use example.
(2) Stakeholder mapping	untested	Teams are relatively small and independent so there's not a lot of inter-org. contact to map.
(3) Rationale capture through integrated links (§ 4.3, §5.1.2)	useful	This is the underlying idea used by the other methods and thus serves as a basic check.
(4) Reuse similar knowledge	untested	Assessing "similarity" between cases poses challenges in finding an example for this.
(5) Requirements management	untested	Some collected aerospace examples use a particular requirements management process that may not fit.
(6) Design Reviews (§ 5.1.3)	has potential	Need more reverse-engineered documents to prove.
New Applications	**Result**	**Additional Notes**
Task-Design maps (§ 5.1.1)	New	Allows a few "power users" who find the maps regularly useful to communicate with others in familiar terms like critical tasks and questions.

5.1. Adapting Mapping to the AEC Context

The focus here will be on differences that seem to have arisen specifically from the building-aero transition. Many variables have changed between the contexts: different software, position of users in the company and current results only represent early work. Some initially proposed methods, like stakeholder mapping, were hard to test. Stakeholder mapping is just not an issue in these small, independent teams. The main successful examples involved connecting tasks to design work, annotating paper-based reasoning and aiding with design reviews.

5.1.1. Connecting Tasks to Design Work (Project Leading)

A new map type was proposed which uses a task network as the top-level view of rationale maps. Whereas aerospace seems to plan work farther ahead, civil engineers seem to focus more on the next upcoming tasks. Perhaps it is because of the numerous disruptions in AEC work such as dropping and resuming projects. In aerospace, new engines or aircraft are rare so fewer suspension opportunities may occur. Further, aerospace designs are so technologically intense and interconnected that resuming a project can require a lot of redesign to incorporate better technologies or modified requirements.

Valuable “wins” created by the proposed approach include: better task prioritisation, improved focus on design and continuous documentation in a form that is immediately helpful in project hand-off. The first two address a comment from one of the interviewees: it is useful to know the information needed from external collaborators a week ahead so that they can be posed at weekly meetings. Some sort of task-issue map makes this more feasible.

5.1.2. Linking Paper-Based work to Design Reasoning

It is worth noting that a fair amount of the aerospace mapping research has been accumulated from a unique environment where trainees are encouraged to work more digitally. The civil engineering example is thus valuable because it provides insights at the other end of the spectrum. One engineer noted that they try to bring the full set of drawings to meetings in the field and send scans back to the office only for records. The primary working medium in the field is paper and a computer-based tool must fit into this or risk rejection.

The proposed mapping method consists of annotating drawings that will have been scanned into the system anyway. The maps thus work as presented in Figure 1: as a map that sits across working documents and serves as an additional place to “sketch” ideas that are difficult to articulate elsewhere.

When designing these new annotations, it is important to keep relevant collaboration info visible. If the drawings are to be used in the field, printing should not hide too much meta-information. A hidden note saves screen space but deletes information on a printout. This aspect of map use in engineering has been around since earlier work in aerospace [18] but features to enable richer linking make it difficult to sustain a practical balance. This application re-emphasises the need for paper compatibility.

5.1.3. Design Reviews and Repositories

The enthusiasm for design review support persisted throughout the study but it is not yet possible to experiment with it. Since “every building is a prototype” there is a clear need for effective review to catch potential problems. Further, the stress involved in defending work and time required for a detailed assessment are clearly sore points among the engineers.

Despite the immature case example, a few leads have been developed on this. In order to reduce the shock of being exposed to an unknown, complicated map all at once, one engineer suggested some sort of filtration mechanism. A map review would then begin with a less overwhelming summary view. Another way around this was suggested by the archive structure. Templates do exist across the company and it may be worth trying to develop one for map navigation. The advantage of these software-based maps is that multiple simultaneous overviews (maps of maps) can be used to navigate a map collection with a few mouse clicks. Conversely, it was noted that the existing folder template structure was not consistently used. Whatever the template, it must balance a degree of standardisation with some concessions to accommodate the variable nature of AEC projects.

5.2. Directions for Dissemination

Based on the above results we will take successful examples forward for further study. The focus will be on refining our existing example scenarios and finding additional champions for the methods.

5.2.1. Refining Example Scenarios

Excellent examples came from the “champion” engineer but moderate-sized maps were unwelcome when introduced to new users at an awkward time. Work needs to be done to find additional suitable cases and, through this collection, assemble enough material to support a design review.

5.2.2. Recruiting Design Mapping "Champions"

Diagramming, in its current state, needs to be championed. It does not seem that it will grow organically because the "activation energy" to get adoption is still too high. Different positions in the company have varying needs for overview and seem to perform different levels of paper-based work at construction sites. The current target for new users is mid-level engineers who have about five year's experience. This insures that they have the experience to see the value in trying different ways of working while still regularly participating in hands-on engineering work. A frequent user of this kind would be in a position to create a core map set that could support a design review scenario.

An alternative idea raised by one of the engineers is to work outside the AEC cycle itself and focus on recruiting clients to demand more transparency in project thinking. The fact that clients tend to lack experience means they have fewer ingrained practices to displace. They also hold the budget which gives them substantial leverage across AEC projects if they can be educated and empowered to use it.

5.3. General Reflections

Despite the widely advocated advantages of integrated digital engineering systems, paper-based work is still the basis of practice in AEC. Some digitization has occurred but it tends to be limited to direct representations of paper without the underlying interconnectivity that digital systems were supposed to bring and despite the substantial investment in infrastructure and effort. Upon reflection, this is a reasonable result to expect. Engineers know their work quite well and their priority is to get tasks done, whatever the process. This motivates them to pull together the most useful aspects of all the tools at their disposal. If anything, it is most accurate to say that work involves increasingly *mixed* physical and digital media. A critical issue then becomes insuring an effective mix by maintaining paper compatibility in software tools.

6. CONCLUSION

This pilot study of mapping in a new industrial context has made initial progress towards supporting more holistic engineering design decisions. Initial studies of document use in past and current projects have demonstrated compatibility between the mapping methods and the new context as well as significant opportunities for future work. Unexpected results, where suggested map methods were difficult to even test, can often be traced to some of the known differences between the industries and they have inspired new methods to fill the gap. Opportunities have been identified in the use of maps to link together annotated documents such as drawings and specifications. This method speeds up communication and resolves problems related to the retrieval of design information. The implementation of this rationale maps not only helps design development and discussion between engineers working on the same project but also communication with reviewers. Study participants have also pointed towards new directions that empower clients and addressing ongoing document management issues. Future work will build on these to support increased competitiveness and sustainability in AEC.

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