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Comparing and Integrating Methods of Design Activity Documentation Across Synchronous and Asynchronous Modes of Collaborative Work

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Abstract
Longer lifecycles and a shifting industrial focus from simple product delivery to through-life support have increased the need to retain organisational knowledge for the duration of product lifecycles and beyond. This fragmentation of work across time and organizations buries organizational understanding of design processes and of the underpinning design rationale in many disparate representations. Further, existing report-based documentary practices tend to omit key information which could compromise an engineer's ability to comprehend and reuse this information in addition to requiring significant additional authoring work.

Emerging approaches to documentation are discussed and compared as cognitive technologies in a snowmobile drive shaft example. One design episode is assisted by interactively documenting decisions in an IBIS-based tool whose output forms the record. Another is passively documented via an activity-modelling approach and media-enhanced records.

This work provides examples of situating discussions about engineering design documentation practices and describes improvements for further development and testing of both the activity-modelling and media-enhanced records and the IBIS-based approaches.

Keywords: CSCW, Media Enhanced Minuting System (MEMS), eXtensible Stylesheet Language Transformation (XSLT), documentation, cognitive dimensions of notation, Design Rationale editor (DRed)

1. Introduction

This paper is about ways to manage the dissipation of organizational understanding by situating digital representations in time, rationale and information flows and by embedding the creation of those representations within regular activity. Problems in retaining organizational knowledge are examined through a comparative study of design process and rationale capture activities on a common design problem. This work explores the need to develop better strategies to retain organisational knowledge due to fragmentation of workflows. Work is split across barriers of time (longer projects, larger asynchronously working teams, and shorter career times at a company), experience and distance (distributed teams and distribution of workflows due to service-orientation) in ways which increasingly involve mediation by computerized systems. In general, current design documentation does not comprehensively capture all information and reasoning within design [1]. Further, in many cases significant process description and supporting rationale may be split among disparate representations [2]. These representations tend to be retrospective and idealised and generally omit key information which obstructs or prevents reuse. Thus, we are seeking improvements in the documentation of design activities and decisions for later understanding and reuse.

This paper describes two approaches comprised of three experimental tools applied to a simple design problem. Transactional and media-enhanced records are used to show how the capture processes can be significantly automated and an issue-based graph tool is used to turn working representations into a rich documentary record of potential solutions. The outcome is examined using the vocabulary and strategies of the *cognitive dimensions* framework [3]. In the end this qualitative analysis finds specific areas for improvement and highlights important tradeoffs to consider when designing these systems. This paper also exemplifies the use of a combined approach to look for gaps and to build tools requirements off each-other.

2. Background – Developing Tools for Capturing Understanding

The fundamental questions posed here is: “How do we capture information such that it is comprehensible and retrievable?” This is difficult to address. Fundamentally, it is not known what will be needed and what will be comprehensible to those uninvolved in the original design. What can be done is to develop new systems which improve on particular weak points of existing documentary systems to explore what is possible in a way that stimulates new understanding of both the potential and the cost of new capabilities. The following sections introduce some of those promising new approaches that are used in this study.

2.1 Media-Enhanced Minuting System (MEMS)

The premise behind MEMS is that traditional text-based minuting techniques are not sufficient in creating accurate representations of synchronous collaborative situations [4]. Much of the rationale and context can easily be lost, making it difficult for users to revisit the records over time and to gain an accurate view of: what was discussed, why decisions were made and what elements were involved in the process. By enhancing the record with selected multi-media, such as audio or video clips and images, it is possible to capture the context in which the decisions and actions were taken and to enhance the capture of informal information not found in traditional meeting records.

The tool itself (Figure 1) is web-based software linked to a repository, allowing the user to easily and rapidly create a record of the meeting in real-time, as opposed to retrospective digital or paper-based minutes. Essentially the software has a three layered structure: an underlying relational database, hypertext preprocessor (PHP) scripts to interrogate the database and a Flash™-based user interface (UI) to input, retrieve and display objects using the PHP scripts as the data translator. Data objects such as images, video, audio and documents are uploaded to the database using the Flash-based “drag and drop” upload form and metadata such as time, date, meeting identifier, agenda item etc. are automatically associated with the data, relative to the specific point in the meeting at which upload occurs.

The PHP scripts convert the object URLs into XML format, allowing the UI to display the data object links as data "blocks" on the meeting timeline. While coordinating the representations in time makes them contextual and much richer; there is a key challenge that, as with all computation-based tools it may be less flexible to use than paper and pen (dependant upon the user and usage environment). However, the advantage lies in that there is no post processing required after the fact, therefore what you capture at the time is the record in contrast to traditional paper and pen needing conversion into digital formats (i.e. typed into word or excel).

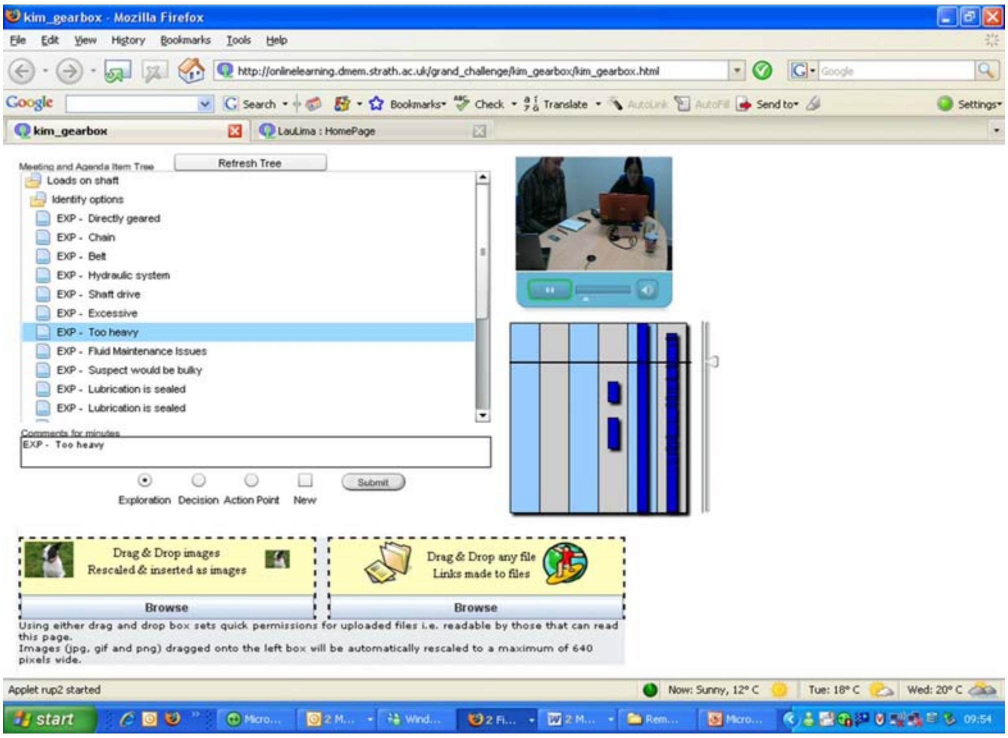


Figure 1. MEMS Flash™ interface

2.2 Design Rationale editor (DRed)

DRed focuses on augmenting discussion and critical thinking by expressing ideas in a graph-based format. The idea is that this representation provides significant advantages for design thinking by structuring activities around more systematic approaches to problems in either individual or group (meeting-based) use. In order to achieve this, it was designed to be as simple as possible so that users can focus on the meeting or task at hand. The tool itself began with a focus on design rationale represented through a system of IBIS-based elements (Fig. 2, right) and has now been extended via a bi-directional hyper-linking system to common applications such as Microsoft Excel (design values are spreadsheet cells in Fig 2, left). A bi-directional link means that a user can navigate back and forth between a particular DRed map element and a specific word or spreadsheet cell in an office document with a single click from either side. This helps by effectively eliminating retrieval time for supporting data and calculations and allowing "unbroken" thinking about the design itself.

Further details of the tool are presented in Figure 2. The left of the figure shows the argumentative graph while the right shows the many mixed elements that can be added such as project tasks (boxes), arbitrary sketches, spreadsheet cells, links to files and "tunnelling-links" that hyperlink to other areas of the map or even to entirely separate maps. The latter keep the arrows from becoming a tangled mess and insure that all map links remain visible on paper print-outs as well. A great deal of development work has gone into DRed's refinement including deployment of an earlier version across a major international aerospace company. Remaining challenges involve the implementation of bi-directional linking to all types of documents on all computer platforms. While feasible, this is not very straightforward. As these maps get larger and more heterogeneous, there is also a significant cognitive design challenge relating to user interface needs for managing complex graphs. A more complete treatment of many of these features is beyond the scope of this paper but can be found in [5].

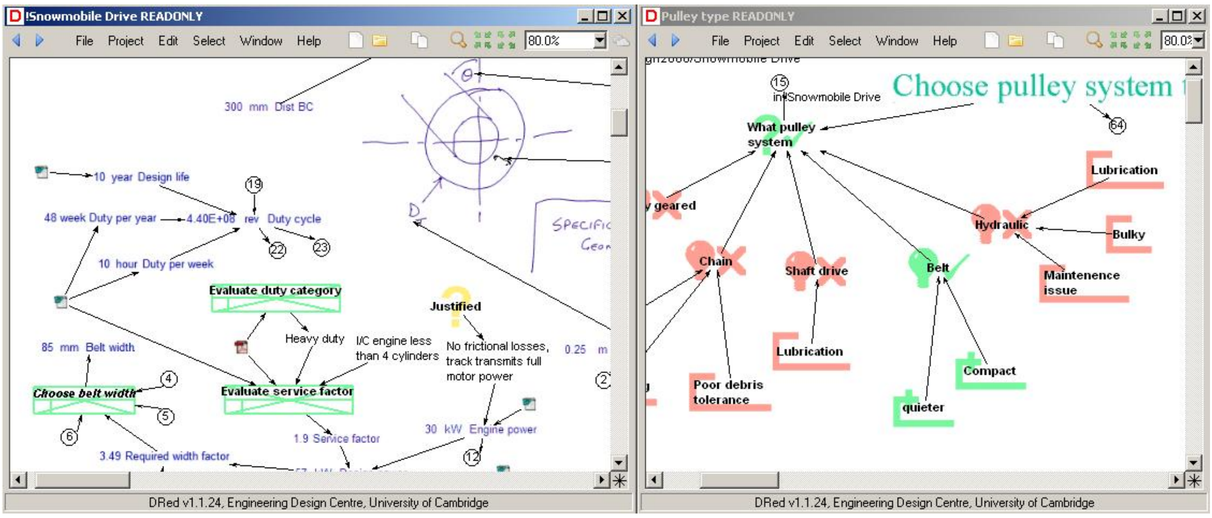


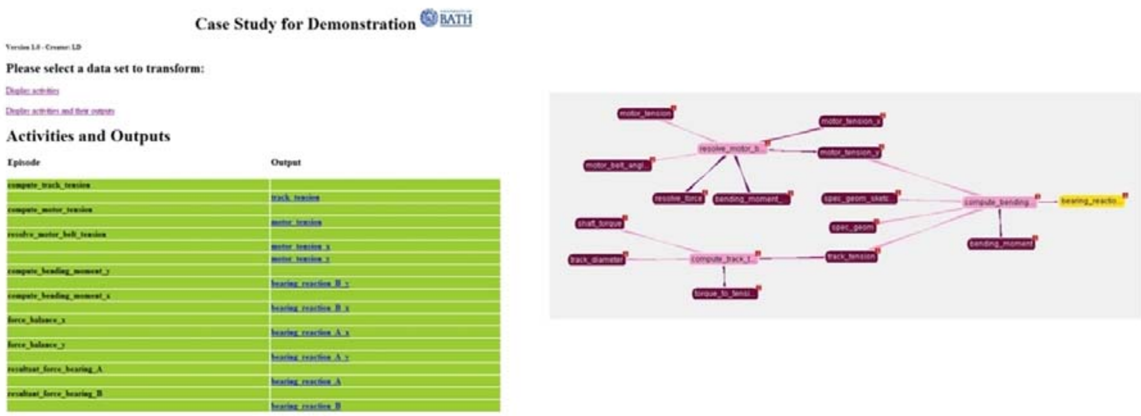
Figure 2. DRed in extended (left) and argumentative (right) features

2.3 Transaction Capture

Where the DRed and MEMS approaches capture the argumentation-based design work, transaction capture seeks to provide a ground-up, automatically constructed record of the processes followed during detailed design. Reports of given aspects of the design activity can be compiled to meet any given reporting need, whether describing the complete detail of a design or providing an abridged or abbreviated report for higher-level reporting purposes. The captured process can also be visualized for more direct exploration and reuse.

Difficulties in retrieving or reusing previous design analyses have been noted in literature and empirically. Scanlan et al. [6] identify the ‘spreadsheet crisis’ in the aerospace industry, where engineers struggle to comprehend the function, content and accuracy of spreadsheet analysis. It has been observed within a multinational aerospace manufacturer that the retrieval and reuse of structural analysis is hampered by the inability to associate ‘working’ analysis files with specific analyses, where reporting documents do not refer to the underpinning activities or their constituent components. This work seeks to provide a record of how such files and the supporting information resources are utilised in a given detailed design analysis activity such that it (and the broader task) may be understood, adapted and reused as necessary.

A client tool has been constructed which allows activities to be captured in $IDEF_0$ form, with explicit references to the inputs, outputs and mechanisms used. The title and location (URL or file path) for each item of information that is utilised in or generated by the activity is entered in an input form. These records are stored on a server as one of a series of XML files. XSL Transforms [7] (a means of translating an XML file into any given representation or layout) are used to construct reports from the underpinning records. These reports reflect a pre-defined reporting need such as a checklist for a design stage gate or a briefing document for a design review meeting. An example of a simple record, describing a series of activities and the outputs from each activity, is given in Figure 3. To augment these records, a browsable map of information flows across activities is constructed by converting each record into a Topic Map [8], as also shown in Figure 3. This map may be dynamically updated to allow an engineer to browse any given design episode in any given form, for example by information flow or by tracing resource utilisation. The links to the underpinning information resources persist in these maps, such that it may be used as a means of retrieval.



XSLT Record

Topic Map

Figure 3. XSL Transform report and topic map of simple design episode

The main challenges confronted in this approach are threefold: linking persistence, aggregation and annotation. The information resources manipulated in detailed design must be addressable for this approach to function. For example, a multinational aerospace manufacturer has migrated structural analysis to a CAE environment which manipulates ‘objects’ of information which are addressable, however this approach must be more broadly adopted for wider capture to be of use. Further, the low-level records must be aggregated. Improved linkages to MEMS and DRed will provide some ‘bounding’ of a design task, as will linkage to a higher-level workflow. Finally, this capture of process may be improved if the ‘know-how’ or rationale is made explicit. Work is underway in allowing engineers to annotate the XSL transforms for this purpose.

3. Methodology

In this research, all three tools were applied to documenting the same design problem. Experience from this activity was then used to inform our evaluation of the different systems. It is clear that these tools represent significantly different approaches to knowledge capture. For instance, one tool aims to sit in the background and transparently collect reusable fragments (Transaction Capture) while another depends on being an integral centre of interaction in order to enriching understanding (DRed). Although analysing the diverse tools appears to be an “apples and oranges” comparison, it is important to note that they are all technologies designed to augment the reuse of design work by capturing fragments from designer’s cognitive activities. The *cognitive dimensions* framework [3] was designed to work in just this type of situation. Although these tools were not developed with this framework specifically in mind, it does provide an established method for evaluating and improving interactive technologies within any medium, from paper to software. It highlights important characteristics of usability which focus on user-interaction and design tradeoffs that are difficult to understand without the kind of cohesive vocabulary of dimensions provided in the framework. For example, it can be challenging to develop a large flow-chart from scratch with paper and pen because the final layout is not known. The diagram will probably go over the side of the page or related elements may end up too far apart. This technology presents a significant degree of "*premature commitment*" on the location of boxes, arrows and text before the whole scope of the diagram is known. Moving to a computer-based diagramming tool allows the free-form, even automatic repositioning of items in a diagram. A disadvantage is that the user cannot freely switch between arbitrary symbols or box types in the way they could by simply drawing on paper. They may have to use a toolbar system or even a customization system to draw non-standard shapes from scratch. By adding to the difficulty of achieving what used to be a simple goal, the computerized tool has increased the "*viscosity*" dimension (see [9] for further examples). Each of 14 dimensions must be evaluated within the context of standard activities. The six activities noted in [3] include things like incrementation (adding to a record), modification (changing information), transcription (moving information between tools), exploratory design (manipulating info to "discover" a solution), search (finding a known target) and exploratory understanding (to discover structure or reasoning).

In this work, cognitive dimensions were used to provide a roughly complete set of categories for rigorous examination of the tools and selected dimensions are used in this paper as points of discussion. The authors selected the *incrementation* activity as the best description of documentary capture. Reuse is a key desired outcome of this collection process and this fits best the *exploratory understanding* activity. Using the literature and our understanding of the problem, the authors created a "profile" for each of these two activities in terms of the effect of the 14 cognitive dimensions after the method described in [9]. Within these profiles, all dimensions were found to have some potential relevance. The most significant of these are presented in Table 1.

Table 1: Discussed cognitive dimensions

Dimension	Description
Viscosity	System's resistance to a user achieving a goal – extra steps, repetition
Visibility	Ability to see components easily, also simultaneously (juxtaposition)
Premature commitment	Constraints on the order of doing things, irreversible decisions required before enough information is available
Abstraction	Mechanisms to operate on a representation's broad structures or properties
Diffusiveness	Verbosity of language or content that confuses the user, uses lots of space
Provisionality	Allows temporary structures of notation to explore behaviour & structure
Closeness of mapping	How closely the system represents a domain or problem in structure or behaviour of elements
Hidden Dependencies	Important links between entities that are not visible, such as equations in a spreadsheet. These create a "search cost" in order to expose them
Progressive evaluation	Allowing a check of the "work to date" to evaluate partially completed inputs, records, activities, structures, etc…

4. Case Study Experiment

As a means of validating and demonstrating the documentary approaches described in this paper, an experimental activity was conducted by researchers within the Innovative Design and Manufacturing Research Centre (IdMRC) at the University of Bath. The chosen activity was the embodiment and detail stages of a snowmobile drive shaft design. This episode features a series of transactions. Computational analysis of the shaft under previously computed loads is used to find torsional and bending stresses. These may then be translated to a combined stress. At this point, a synchronous activity is undertaken where these stresses are considered in light of material properties and design factors (again previously computed) such that a decision may be made to reconsider any aspect of the design should it be subjected to excessive stress. At this point, the previous transactional activities may be repeated to ensure that the updated design meets the structural requirements. The structure of the experiment was as follows:

- Matlab served as the analytical engine for each transactional activity, and the method used was stored as a separate information resource which could be applied to identical tasks performed at other points in the design process.
- Parameters and instances of information generated in each activity were stored in an XML file such that later activities could refer directly to the information of interest.
- A script converted information entities into the right format for Matlab methods.
- Upon encountering a synchronous activity, the information required for these activities was presented in its native format.
- The XSLT templates necessary to present this information in a more readily comprehensible manner were identified and retrospectively created.

4.1 Capture Method 1: Transaction Capture & MEMS

Transaction Capture is intended to run in the background, with no user effort, besides that initially needed to integrate activity capture within CAE environments and to construct the XSLT templates. At present, the activity records are created manually using a form-based tool, with attendent burden upon the user. The XSLT records and Topic Maps may be automatically generated at any point during the design. The use of MEMS has a negligible effect on the experiment as it is not directly involved; it's more of an objective, stand-off software which records what happened in real-time as it occurs. As with all computation based tools it may be slower to use than paper and pen (dependant upon the user) but the advantage lies in that there is no post-processing after the fact, therefore what you capture at the time is the record in contrast to traditional paper and pen being converted into digital formats (i.e. typed into word or excel) for virtual storage. The uploading of video to MEMS for this experiment required manual conversion into flash format to allow for display on the flash interface which took a little bit of time (ranging from 15 secs to 3 minutes depending on video size). A converter is in development which can do this automatically (and much faster!) when you upload any video file to the system. A pre-condition of using MEMS is that an active internet connection is necessary to communicate with the database. Authors are currently aiming towards developing a "working offline" mode which stores the data objects locally then as soon as a network connection is available synchronises the data objects with the database.

4.2 Capture Method 2: DRed Document Integration

The experiment's documentary work was repeated in DRed to create a browsable, interdependent network, pictured in part in Fig. 2 (left.). This system carries the bi-directional interdependencies between the tool and applications so that new values can be entered for successive iterations, enabling groups of operations to be repeated. Taking the assignment as a whole, DRed is considered roughly competitive with the paper and pen portions of the experiment: designing, preparing for reviews and documenting the work sufficiently well for it to be assessed at some future date. Doing calculations by spreadsheet is easier than with a calculator, particularly taking into account the need for repetitions to check for entry errors. Interaction is a bit tedious when manually linking each new dependent variable between Excel and DRed and then manually linking to its independent variables. It is proposed that the evolving dependency structure of the design space is far clearer in DRed than multiple pages of notebook. There is also payback in the reduced need for the preparation of further diagrammatic material for presentations and reports. Once you start iterating using the DRed or XSLT approaches, there is great economy in not needing to re-describe calculations. Making the task elements sensitive to changes in their input parameters (ex. when exceeding a threshold) to signpost when the task needs redoing would guide the designer better than trying to manually track the need for rework tasks. Industrial experience, for example, shows that post-hoc design reports can be significantly shortened if design was performed using DRed.

5. Dimensions in Comparison, Integration and Extension Discussion

The complete details of analyses in all dimensions, tools and would constitute 48 points of descriptive comparison. This is beyond the scope of what is presentable in this paper. This section focuses on particular dimensions and trade-offs that were highlighted during our investigations. The definitions of the dimensions that are discussed below are presented in Table 1 in Section 3.

5.1 Trends and Contrasts

An important theme is found in how these tools affect the *viscosity* and *visibility* dimensions in both exploratory understanding (reuse) and incrementation activities. Both MEMS and Transaction Capture seek to greatly reduce the *viscosity* associated with creating a documentary record. There is a clear push to remove the reporting work that is considered an impediment to getting more critical work done. These tools create richer records where they would not exist otherwise, and in doing so, they make much of the work *visible* for later reuse. That in itself is a very reasonable goal, however that gain comes at the cost of some *premature commitments* in terms of setup for encoding by computers. This trades off with the need to control that *visibility* lest it creates a *diffusive* representation. Exploratory understanding activities in either DRed or Topic Maps demonstrate this issue in this experiment, although Topic Maps present a partial solution by allowing a user to dynamically update their viewpoint, either traversing or extending the visualised activities along a given axis of interest. DRed has a significantly different approach. Not only does it avoid doing much recording automatically, but it requires constant, focused interaction during the use process. The idea here is that, as a hyperlinked record, it *maps* very *closely* to the structure of thinking of the particular problem at hand, in a synchronous group setting, it provides a means of *progressively evaluating* an agreed-upon overall result of discussions. When it becomes necessary to manually link, our experiences in general tell us is unlikely to be done rigorously, if at all. The “design manoever” among the cognitive dimensions is thus to outweigh this *viscosity* with advantages in *visibility* and *progressive evaluation*. Ultimately, the *viscosity* that DRed seeks to reduce is not directly in the use of the tool but in the sense-making effort of each individual to understand the collaborative activity. Similarly, MEMS encourages review and update of agenda content as work progresses, but it is constrained to only explicitly represent temporal relationships between linked media. *Visibility and juxtaposition* is leveraged to reduce *viscosity* for reuse. The extended hyperlinked record in DRed enables fast navigation to the precise location in documents where relevant arguments or equations are found, virtually eliminating the *viscosity* of constant retrieval work. Similarly, the implementation of linked timelines in MEMS allows users to navigate through the timeline and recall all objects associated with any given time within the meeting.

These approaches both manage and generate a lot of information. As mentioned above, this can create a great deal of *diffusiveness* if one attempts to represent all of the information at once. Each tool presents a different method of dealing with this. XSLT methods rely on automated filters in the visualization system to lay out the structure of the content and to filter the details into standard reports. In other words, it *abstracts* the control of the content. DRed, by requiring constant accretion over the course of activities, is not finalized until the activity is finalized. Its content retains a high degree of *provisionality* throughout its use and only the relevant argumentative content survives in the record.

The various approaches are valuable in how they *abstract* different elements of work, from hiding the recording activity below the computer interactions to providing more parametric ways of interacting with records to intricate hyperlinking in the place of more manual retreival references. One of the difficulties noted in the literature is the potential of an “abstraction barrier”, a minimum number of abstractions that must be learned in order to even begin to use a system [9]. This plays out in XSLT since, all of the tools it connects to must be understood in order to design the target reports. Adding report types may require a significant review of the system. The *absrtaction* has lead to an infrastructural *commitment*. In all cases, abstraction of navigation via hyperlinks creates *hidden dependencie*s which can very easily interfere with reuse activity if, for example, the links are broken. It will not be obvious at first glance what went wrong; the effort required to root out the hyperlink and manually retreive lost content confirms the idea of “search cost” associated with *hidden dependencies* [9].

5.2 Closing the Gaps: Guidance for Combination and Outstanding Limitations

As it stands, Transaction Capture is relatively weak without capturing the reasons why the particular activity or series of activities were undertaken. Conversely, the utility of both DRed and MEMS could be vastly enhanced by capturing the detailed processes that led to decisions captured in these tools. Ultimately, none of these methods are necessarily mutually exclusive and the resulting overlaps of documentation if they were all combined would probably depend on the particular scenario. There are a whole range of reuse cases, of which the design scenario is only one. The main mechanism of combination relevant to this discussion, then, is the reuse of “design manoeuvres” present in each tool to help spread the advantages that each one has or to remedy limitations present across the board.

The *provisionality* that helps to handle *diffusiveness* in DRed for incrementation can potentially be transferred to reuse activity as well. Instead of learning by reading a document and taking notes separately, this system seems conducive to signposting one’s navigation in order to achieve the same kind of clarity sought in the initial creation of the record. This could take the form of additional temporary notes, a “note taking” map or a browsing history. This would also permit better *progressive evaluation* of reuse since the user would be better articulating what they learned.

There remain some more aspects where viscosity could be reduced by various *abstractions*. DRed as a whole with Word and Excel linking may be coming up against some difficult barriers in terms of scaleability. Manually shifting a DRed map’s nodes to make room as the design space grows unpredictably is difficult. There is definite scope for some kind of auto-layout to support this; however the tool is grounded in human-operated *progressive evaluation*. This suggests the need for some degree of automation that is applied incrementally and mixed with user input. A potential solution is presented in [10] in the form of parametric graphs.

Finally, there may always be limitations in tools with respect to general scalability. A priori organisation and filtering is preferable to point-of-need querying to keep data useful and manageable in size. The resultant *premature commitment* embodied here was mentioned above. Low level capture (like XSLT transforms) allows more flexible representation of higher-level structures to fit any given need, but this recombination is less than straightforward. A library of such views may be constructed, and 'dropped over' the underpinning records, but currently, this means most of the report types need to be specified ahead of time. It is difficult to know which level of granularity to commit to and only further experimentation will suggest better heuristics.

6. Conclusion

Heterogeneous tools, varying on the spectrum of synchronous to asynchronous modes of working, were presented and grouped into two approaches. They were applied to an identical design activity to gain experience on the cognitive dimensions that they affected. This work provides an example where a framework was applied to examine functional shortfalls in design practice as documentation technologies evolve. Some design manoeuvres in the documentation process were presented to help further the maturity of the approaches.

Further work includes the general development of each tool, testing and evaluation by new users as well as using these findings to guide specific tests of empirical instances of revealed issues. The ambition of this work is to learn to match each approach to the most appropriate design situations. At the same time, researchers must be mindful of their assumptions in tool development. Industry is doing things successfully. One must ask, then, what really needs improving? Research needs to model better when decisions need reuse and why. Our work is not a complete perspective of all the "loci of design knowledge" which includes people, processes (of which tools are a part) and products [11]. Everything of relevance is clearly not articulable via information capture alone, however these experiements have demonstrated, and hopefully extended, the boundaries of what is possible.

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