Technical University of Denmark

The role of logbooks as mediators of engineering design work

McAlpine, Hamish; Cash, Philip; Hicks, Ben

Published in:
Design Studies

Link to article, DOI:
10.1016/j.destud.2016.10.003

Publication date:
2017

Document Version
Peer reviewed version

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Please cite this article as: McAlpine, H., Cash, P., & Hicks, B. (2017). The role of logbooks as mediators of engineering design work. *Design Studies*, *48* (January), 1–29.

Highlights

> We explore the mediating role of logbooks in engineering design.

> We report two studies of PIM use to explore mediation.

> We propose three key mediation modes simultaneously supported by logbooks.

> We identify implications for design of new PIM tools and practices.

Abstract

Information transformation is key to engineering design work. However, research on how information management tools, and logbooks in particular, mediate this, is fragmented. We explore this via two studies (from which we confirm the central role of logbooks) and propose three modes of mediation: facilitating cognition and creation, gathering and collation of information, and staging and transformation of information. The findings explain the widespread use of logbooks through their support of these three modes. Consequently, we contend that multi-modal mediation is one of the main reasons why logbooks are such a central and enduring medium. This synthesises and extends theory on mediation and information use in engineering design. Further, practical insights are derived for the development new information management tools.

Keywords: information processing; design knowledge; reflective practice; logbooks; reflective practice

This paper identifies and explores the key role of engineering logbooks in mediating engineering design work. However, in order to support this re-evaluation of the role of the logbook it is first important to understand current perspectives, and how mediation could be interpreted in this context.

Knowledge-intensive industries such as engineering design may be viewed as an information-transformation process with information from multiple sources gathered, integrated, transformed, and used to create an artefact (Hicks, Culley, Allen, & Mullineux, 2002). In support of this, there have been considerable advances in the management of formal design information in, for example, Electronic Document Management (EDM) (Hendley, 2012) and Product Lifecycle Management (PLM) systems (Siemens, 2015). Their success can be attributed to a combination of significant technical (computational) improvements made over the last few decades, e.g. more sophisticated ways of organizing and accessing information (Baeza-Yates & Ribeiro-Neto, 1999), and the adoption of standard information representation and exchange formats. Further, tracing the flow of 'formal' product and process information contained within, for example, Product Lifecycle Management (PLM) and other document management systems is now possible. However, understanding regarding the roles of tools dealing with informal information is less well developed (Topi, Lucas, & Babaian, 2006). In particular, the majority of research in this domain has focused on logbook use due to its assumed special role. Thus there are two key research needs in this domain: to confirm and contextualise the centrality (or otherwise) of logbooks, and to explore the relationship between informal and formal information use with particular reference to the logbook.

With this in mind, and taking a starting point in the literature surrounding logbooks a review of their use in engineering design is conducted (Section 1.1). Based on this a number of questions are raised as to the assumptions underpinning the prominence of logbooks and their role(s) in engineering information work (Section 1.2). This sets the stage for two empirical studies that elucidate the wider landscape of information tool use, including logbooks (Section 2) and subsequently explore the relationship between the logbook and formal information (Section 3). Finally, the findings from the two studies are considered collectively in order to reveal and elucidate the role of the logbook. Wider implications for both theory on information use in engineering design, and the development of information support tools in practice are also developed (Section 4).

1. Information Tools in Engineering Work

This section outlines the current state of the art in research on informal information tools in engineering design work, with a focus on bringing together and contrasting prior empirical work in this domain (Section 1.1). Based on this review a number of research questions are defined and an empirical methodology derived (Section 1.2).

1.1. The Many Roles of the Logbook

In contrast to the large body of work dealing with formal information and its management, less research has been undertaken in the field of, what can be termed, informal information management, especially in the engineering domain. This is despite a growing recognition of the importance of informal information as a means of accessing tacit knowledge through processes such as socialisation, externalisation, and combination (Nonaka, 1994). Topi et al. (2006) also note that informal notes remain a "*largely untapped resource*".

One type of informal information that forms the basis for the majority of the research in this area and is almost ubiquitous in the engineering domain is the engineering logbook, or notebook – usually consisting of notes, sketches and calculations, and other information gathered in support of the engineer's day-to-day work (see, for example, McAlpine et al. (2006) and Sobek (2002)). In addition to the physical affordances of logbooks (paper robustness, ease-of-use, co-creation etc.) their pervasiveness is attributed to a number of pragmatic factors (explored in more detail below):

1. Use is trained at both the undergraduate and professional level.
2. They contain information indicating design intent and the development of rationale.
3. The content often retains its significance and allows for re-examination.

With respect to the first factor, authors have argued that logbooks are very widely used because they are one of the only types of informal information management tool in which engineers receive any structured training. For example, Oehlberg et al. (2009) notes that logbooks (or "*design journals"*) are referred to in teaching material such as engineering textbooks. It is also a requirement at many universities that engineering students keep a logbook for certain parts of their course, to both encourage "good practice" and to allow the instructor to better assess the students' progress. Many organisations also mandate the use of logbooks to ensure a record of the development of ideas for intellectual property claims (Hyman, 2003), with Oehlberg et al. (2009) arguing that this role as a legal record "*is often* *what prompts a company-wide policy mandating that the entire organization adopt formal design journal practices".*

With respect to the second factor, logbooks contain information that can be considered to provide evidence of design intent, alternatives, and rationale, such as sketches, calculations, and meeting notes (McAlpine et al., 2006; Sobek, 2002). The importance of this content is illustrated by Subrahmanian et al. (1997) who show that *"design history and rationale are continually being lost and that this loss can result in the need to recreate the rationale of a design. This reverse engineering process can lead to repeating the same mistakes and failures encountered during the original design process"*. Indeed, the *"pitfalls of paper"* are estimated to cost the pharmaceutical industry $1Bn annually in repeated work (Butler, 2005).

Finally, the potential significance of the content of logbooks is further developed by the historical importance of logbook-type material, with much of what is known about engineers and inventors of the past extracted from their historic working papers and notes. Perhaps the most famous example of this are the notebooks of Leonardo da Vinci (2012). From his notebooks, it has been possible to understand some of his designs and even reproduce them. Similarly, the National Cataloguing Unit for the Archives of Contemporary Scientists (NCUACS, 2009) continues to archive logbooks and other personal material from more contemporary engineers and scientists, such as Sir Frank Whittle, for historical research.

Despite the identification of these pragmatic factors more fundamental explanations as to why logbooks (as apposed to other emergent informal information tools e.g. email) are apparently so central to, and persistent in, engineering work are fragmented. As a consequence, logbooks are assumed to be important but there is little agreement as to why this is. Further, works have typically focused on logbooks in isolation, with few contextualising studies comparing them directly to other informal information management tools (McAlpine, 2010). In particular there has been significant research examining logbook practice and the creation and testing of electronic logbooks (e-logbooks). Whilst a detailed review of e-logbooks is outside the scope of this paper, the descriptive studies that informed their creation are relevant. An overview of this research is given in Table 1, which describes a range of studies indicative of the varied perspectives found in the literature. The majority of extant research has considered either the underlying informational structure or user practices, with little attention given to the fundamental role of the logbook in the wider context of the design process and the engineering designer's personal information space.

For the purposes of this research, the engineers' personal information space is considered to include both their personal and project level information tools and systems. This includes (but is not limited to) diaries, notebooks, sketches, CAD, email, reports, Product Data Management systems and presentations. Consistent with contemporary literature the term Personal Information Management (PIM) is used throughout this work.

Table 1: Summary of research into logbook practice

Author	Nature of Study	Domain	Key Findings
Wilcox et al. (1997)	Artefact walkthrough with 11 knowledge workers, investigating logbook type, structure and organisation.	Knowledge work (general)	Users interviewed expressed frustrations with paper-based notebooks in terms of organisation and retrieval of important information, and lack of ability to dynamically re-organise notes, but valued ease of use and free-form input pen and paper provided.
Schraefel et al. (2004)	Evaluated nature of logbook-as-artefact via a user-centred study of chemists' paper-based note-taking practice (interviews + ethnography).	Chemistry	Lab notebooks have utility as both a recording device and as a 'personal journal'. Explored the functional and experiential properties of current note-taking practice and tested a prototype electronic notebook. Users responded positively to the ability to structure, retrieve and share their records.
McKay et al. (2009)	Participatory design of enhanced logbooks for biologists via brainstorming and workshops.	Biology	Identified that research biologists use a wide variety of paper-based and digital sources, collating this information in logbooks. They required better integration between paper logbooks and on-line material. Found that logbooks "are both a personal record and a public document", and contained large amounts of mixed-media material. Prototype 'augmented reality' logbooks created and tested to explore various facets of the links between paper-based and digital materials.
Wood et al. (1998) **and Yang et al.** (2005)	Thesauri-based classification of web-based logbook information (called PENS – Personal Electronic Notebook with Sharing) to aid retrieval.	Engineering /Design	Wood et al. used both electronic design logbook contents, CAD drawings and formal diagrams to create a thesauri-based Design Information Retrieval (DIR) system, concluding that "The use of a thesaurus of function/component terms derived from design notebooks performs better than a thesaurus derived from formal final reports.", with Yang et al. reporting "…markedly (10-50%) better precision at the same values of recall than formal information."
Liang et al. (1998)	Study comparing re-use of electronic logbook notes (PENS) and three other sources of more formal information (emails, slides and reports) created over several years.	Engineering /Design	Showed that "… capture of the information takes place best when several channels of varying formality are made available, thus casting as wide a net as possible over the information that is generated in whatever format." Also showed that PENS (logbook) information was the most extensively re-used within teams working in the same year.
Sobek (2002)	Analysis of nature and content of 21 undergraduate engineering logbooks in terms of quantities of concept, system and detail representations created.	Engineering /Design	Showed that engineering logbooks were used extensively at the conceptual and systems levels, revealing that "…at the conceptual and system levels, written word and hand-drawn sketches account for 80% of the occurrences" and that the students still "…depend on hand-drawn representations a great deal as they explore problem and solution spaces, despite the prevalence of computing tools".
McAlpine et al. (2006)	Analysis of 16 engineering logbooks for structure and content, survey exploring the purpose of keeping a logbook.	Engineering /Design	Found that logbooks were commonly kept as a personal record of work, and to remind the engineer of work-in progress. 26 different types of information identified in logbooks, demonstrating multi-media content.

Oehlberg et al. (2009)	Longitudinal study of 'design journals' from graduate-level product design course, coded for level of sketch detail, and whether journal was 'tangible' (paper-based), digital, or a hybrid.	Engineering /Design	Reviews literature on purposes for keeping logbooks, grouping the reasons into i) to support IP protection, ii) for mobility (i.e. the ability to take their logbooks with them when travelling), iii) as effective 'Centralised personal information storage' (i.e. being able to keep lots of types of information in one place), and iv) to support reflection. Identifies the importance of design journals in supporting thinking and makes a series of design recommendations to ensure 'next generation' design journals support this mode of use.
Currano and Leifer (2009)	Survey of 30 students, investigating their experiences of using 'idealogs', the methods they used, what they recorded and why.	Engineering /Design	Found that "Subjects reported a strong understanding of idealogging as a tool to help create and develop ideas." And further, that "Designers use sketches to externally visualise formerly abstract ideas, and the sketches reflect their ideas back to them in new ways, enabling a reflective dialog between the designer and their ideas."

1.2. Framing and Methodology

Unpacking the research highlighted in Table 1 as well as the wider logbook literature, it is broadly assumed that logbooks have an important role in many engineers' working practices. In particular, there is general agreement in the literature about their role in supporting the recording of various information types and the subsequent creation of other informal and formal documents. Further, the three pragmatic factors outlined in Section 1.1 are widely acknowledged. Existing studies (c.f. Table 1) have typically focussed on investigating specific information structures and associated activities (e.g. sketching, communication, and documentation). For example, Currano and Leifer (2009) describe numerous aspects of logbook use, as well as their more general role in the design process and in support of design thinking. However, across the literature there is little consensus on the mechanisms underpinning the various roles of logbooks or how these might be brought together to explain logbook use more generally.

Currano and Leifer (2009), Oehlberg et al. (2009), and Sobek (2002) all describe perspectives on logbook's as an intermediary between thinking and design development, particularly in the form of written output (i.e. sketching or notes). In contrast, Schraefel et al. (2004) focus on logbooks as a flexible external memory. Taking this memory concept further, Wilcox et al. (1997) and McKay et al. (2009) describe logbooks as a means of organising and sharing information. Wood et al. (1998) and Yang et al. (2005) operationalize this by using logbook notes to create repositories of otherwise fragmented information. Finally, Liang et al. (1998) also deals with the repository perspective but describes how this can underpin the accumulation of information and its subsequent transformation from informal to formal.

Based on this review it is possible to conclude that there are a number of conflicting perspectives, which although fragmented can be logically linked through common themes such as memory and facilitation of thought. Further there is a wider need to confirm and contextualise the overall importance and apparent centrality of logbooks in personal information management. In order to bring this disparate body of work together two major questions need to be answered:

- How do logbooks fit into the wider landscape of personal information management?
- How can the varied descriptions of the mechanisms underpinning logbook use be reconciled in a singly coherent framework?

In order to answer the two questions outlined above a two-stage research approach is adopted. First, the role of the logbook in the wider context of Personal Information Management (PIM) is characterised through a survey and interviews with practitioners. This details the use and interconnectedness of PIM tools in order to contextualise and evaluate the importance of logbooks in relation to e.g. email, and to establish any key differentiating features at this level of analysis e.g. unique patterns of use. This answers question 1 above. Second, logbook information content is examined in more detail. This employs an established method to classify the type and nature of logbook information content and contrasts this with more formal reporting. This second study allows for the fragmented perspectives highlighted in this section to be considered in a single study, thus facilitating their synthesis into more general insights. This answers question 2 above. The following sections describe each of the studies including details of the methods employed and descriptive results.

2. Study I: The Engineering Designer's Personal Information Space (PIM tools)

This study used interviews with practitioners to characterise the use and interconnectedness of Personal Information Management (PIM) tools. As previously noted, PIM describes any information tool used by the practitioner whether informal or formal. This includes logbooks as well as more formal outputs, such as engineering drawings, work instructions and reports of analyses or test results, and builds on the work previously reported by McAlpine et al. (2011).

2.1. Method

Twenty-seven practicing engineers were interviewed, representing a cross-section of levels of experience, job role, and types of industry in the UK. These were split between engineers from large companies and Small to Medium-Sized Enterprises (SMEs). Further, both design stage and manufacturing/in-service were represented, with around 30% (mainly from SME's) working across the entire product lifecycle. All the engineers were interviewed in-situ in their organisation. The population was selected in order to provide a broad overview of PIM practices in engineering work in the UK, and allow for evaluation of PIM use across a range of contexts. Table 2 summarises the nature of the participating organisations. Although the various organisations enforced different policies regarding logbook based record keeping, this did not substantially influence the final results of the study.

Table 2: Summary of interview participants

Nature of organisation	Type of organisation	Number of interviewees
Aerospace design and manufacture	Large multinational	4
Packaging machinery	SME	4
Aerospace design and manufacture	Large multinational	6
Precision components	SME	5
Aerospace design	Large multinational	1
Pharmaceutical manufacture	Large multinational	1
Automotive components	Large multinational	1
Academic (University)	Large UK-based	3
Medical devices design and manufacture	SME	2

The interview study was split into two stages. First, demographic and contextual information was gathered for population characterisation purposes. This included experience, job role, level of qualification, and lifecycle stage(s) over which participants mainly work.

The second stage used a semi-constrained concept mapping exercise to describe what informal and formal information types and tools were used. The appropriateness of this type of approach has been previously validated by Johnson and O'Conner (2008). Participants were asked to create a map of their 'information world' – identifying what information types they used (both informal and formal), and how they were used, in terms of relationships between types i.e. where the information in one tool/source was re-used or contributed to another.

As previously stated, a semi-constrained concept mapping approach was adopted to aid participants in describing their 'information world'. This was based on a pilot study where it was found that participants under-reported the number of sources of information used when un-prompted. Consequentially, the maps were pre-populated with various types of informal and formal information, derived from previous works (Court, Ullman, & Culley, 1998; Lowe, McMahon, & Culley, 2004; McAlpine et al., 2006). Participants were able to add additional concepts in accordance with the defined method (Johnson & O'Connor, 2008). Participants were also asked to talk through the nature of each link (i.e. how and why it was created) in order to provide deeper context when analysing the map. To illustrate the method and demonstrate the complexity of the captured data, a typical map is shown in Figure 1. Note the pre-populated concepts printed on the paper (separated into formal/informal by the dashed line), and the additional concepts added by the participant. Further, the participant has represented the direction of information flow using hand drawn arrows. Examples, of information use in each block are elaborated further in Study 2 (Section 3).

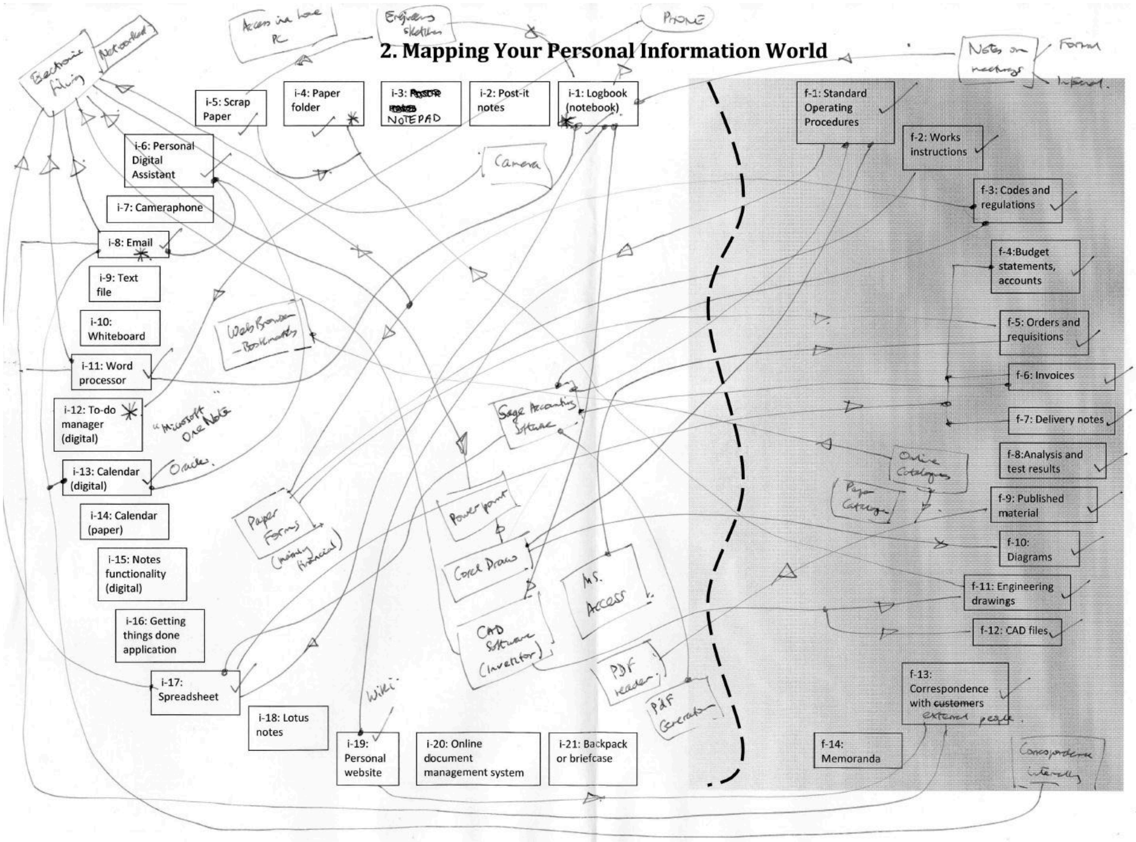


Figure 1: An example of a completed 'Information world' exercise

Analysis of the completed maps focused on identifying the most used concepts i.e. those highlighted as relevant by most participants, and the level of connectedness between concepts i.e. the number of links associated with any concept.

2.2. Results

For the purpose of this paper, the results of Study 1 are used to examine the two major assumptions underpinning extant research on logbooks; namely that logbooks are widely used and highly interconnected with other information tools. Both of these assumptions are confirmed by the results from Study 1. Analysis of the maps yielded three main findings. First, logbooks were one of the most commonly used information management tools, with every participant highlighting this element. Here, logbooks, email, post-it, digital calendar, and spreadsheets were the most used informal tools, as illustrated in Figure 2. Logbooks in particular, were used significantly more ($p < 0.05$, 2-tailed students t-test) than all informal tools ranked below Paper Folder. Figure 2 shows the most used PIM tools (cut-off = 10) with informal tools being highlighted in black. The most used PIM tools were also found to be relatively consistent across the different job roles considered in Study 1: manager, designer, industrial researcher.

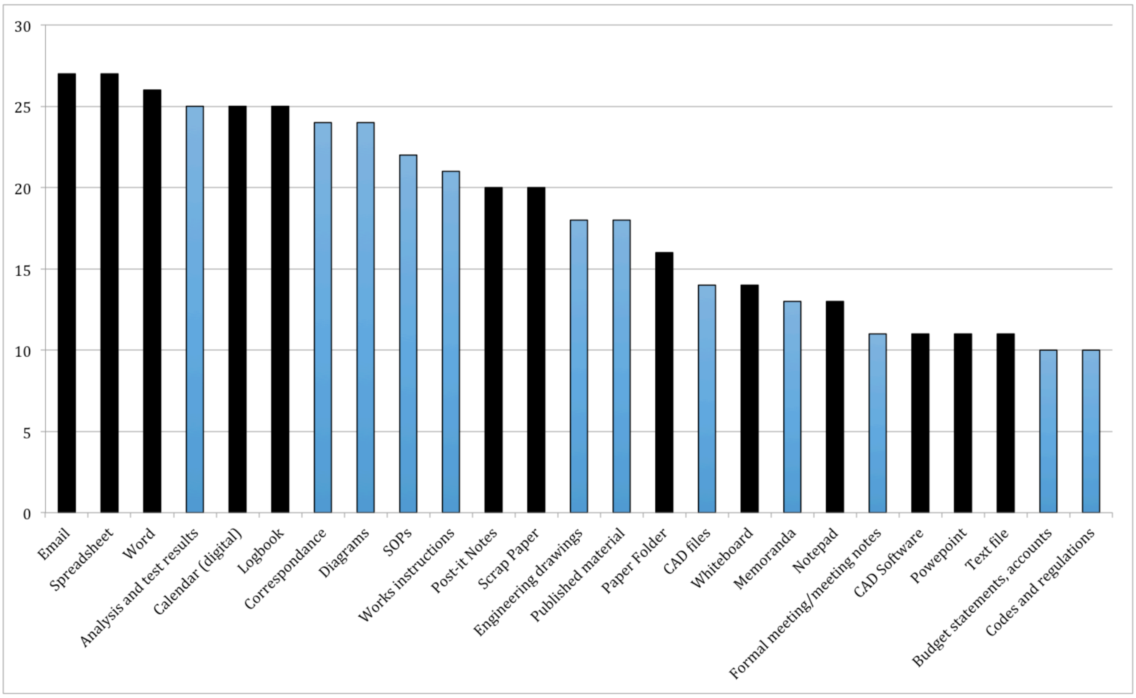


Figure 2: Distribution of PIM tool use, informal tools highlighted in black

Second, logbooks were the most interconnected type of PIM tool, being connected to 139 formal and informal tools and outputs. Specifically, they were linked to 92 formal and 47 informal sources. Logbooks were significantly more connected ($p < 0.05$, 2-tailed students t-test) than all tools ranked below Word. The range of tools and outputs identified suggests that these findings represent a relatively complete set of PIM tools likely to be encountered in engineering design work, particularly given their alignment with prior studies (Section 1). Figure 3 shows the most connected PIM tools (cut-off = 10) with informal tools being highlighted in black.

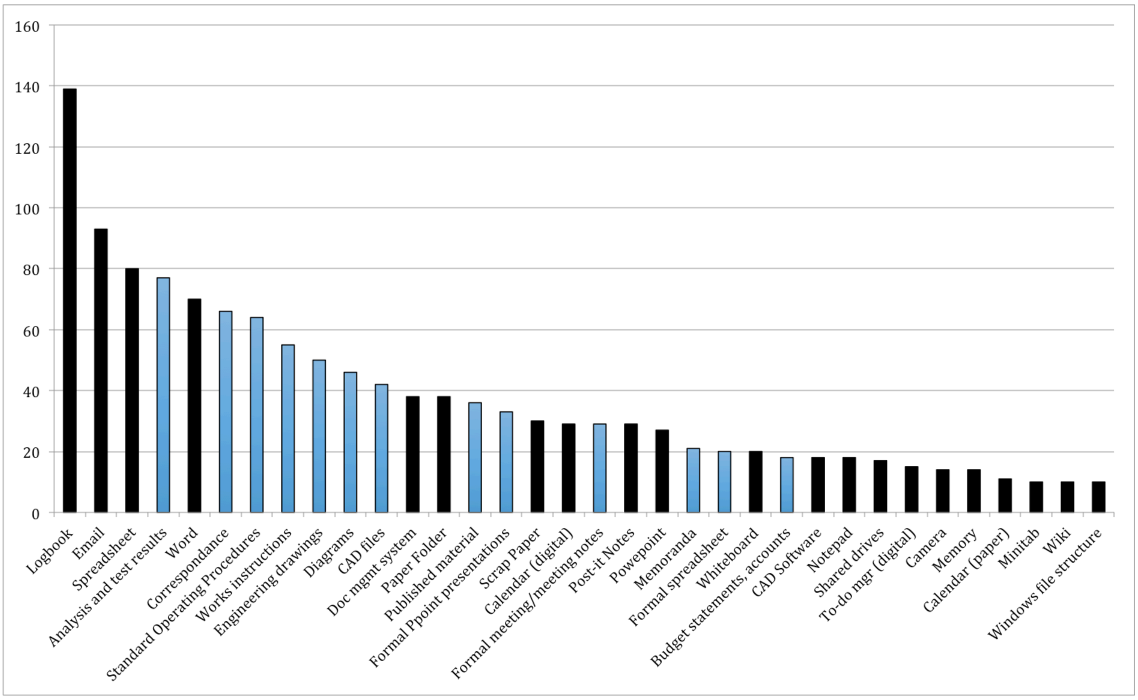


Figure 3: Distribution of PIM tool connectedness, informal tools highlighted in black

Third, exploring connectedness further, logbooks were found to be a central PIM tool, with more connections to a wider range of sources than any other tool. Figure 4 illustrates the number and distribution of connections between the most used Formal Documents and Informal Tools. This decomposes the overall results from Figure 3.

Formal Documents

Informal Tools	Analysis and test results	SOPs	Correspondence	Works instructions	Diagrams	Engineering drawings	CAD files	Published material	Formal PowerPoint presentations	Formal Meeting minutes	Memoranda	Budget statements	Orders and requisitions	Formal spreadsheets	Technical reports	Technical documents
Logbook	14	11	7	8	10	6	5	2	4	7	4	2	2	2	3	2
Email	4	2	21	4	1	1	2	5	3	4	6		1	1		1
Spreadsheets	11	1	4	3	2			1	4	1	1	8	2	7	1	3
Word	2	9	3	8	4	2	1	5	1	1	1	1	1		1	3
Doc mgmt. system	1	6	2	6	2	4	4	4		1			1		1	
Paper Folder	4	4	1	4	3	3		2		1	1	1		1	1	1
PowerPoint	3	1	3	2	2			2	9						1	
Scrap Paper	4	2			3	4	1			1				1		
CAD Software				1		2	13									
Whiteboard	2	2	1	1	2				1	3				1		
Calendar (digital)		1	5	1				1		1	1	1				
Memory	1	1	1	1	1	1	1	1			1	1	1			
Post-it Notes	3	2	1		1	2	1				1			1		
Notepad	2	2			4	2	2				1					

Figure 4: Decomposing connections between formal documents and informal tools

Bringing these perspectives together (usage, connectedness, and centrality) it can be concluded that logbooks do indeed occupy a unique position in the landscape of personal information management. In particular, their high connectedness and centrality indicate that they provide an important mediator for other information tools. This is evidenced by the 139 total links between both formal and informal sources, and also between informal and formal outputs (as evidenced by the 92 links between logbooks and formal documents). As such, Study 2 will investigate what mechanisms underpin the central role of logbooks in PIM.

3. Study II: An intra-record comparison of logbooks and formal technical documentation

As previously stated, a second study element was undertaken to give deeper insight into logbooks' information content, and in particular, their relationship to the information in formal technical reports. This builds on the work previously reported by McAlpine et al. (2009).

3.1. Method

Six engineers studying mechanical engineering at a UK University generated the documentation used in this study. Each student was in the final year of a master's level engineering degree and had at least one year of industrial experience. As such, they were not completely novice designers. Further, Cash et al. (2013) found the work of a similar student group to be comparable with more experienced engineers. The documentation consisted of logbooks, reports, and CAD drawings, and was generated during a three-month project carried out in conjunction with a large UK-based engineering organisation (industrial sponsor). Although the team members predominantly undertook engineering design work, there were elements of research work and a project manager's logbook that recorded the team responsibilities in terms of members and tasks, meetings etc. All students were in

The industrial sponsor's role was as the customer i.e. they gave the team a design brief, and provided resources and access to facilitate the project. The brief was to re-design a module for a large packaging machine in order to reduce changeover times. The six team members had all worked for at least one year in industry and in a variety of sectors. This project was chosen for three reasons. First, the dataset was relatively complete and self-contained. Although there were some associated project emails notes/sketches that were not captured (e.g. temporary sketches made on a whiteboard), the dataset represented almost all of the physical record. Second, the engineers did not know in advance that the documents would be analysed, which was essential if meaningful comparisons were to be drawn. Thirdly, it represented a 'real' industrial problem, with engagement from a range of stakeholders and tasks spread across various design stages – from defining the problem to detailed design. Based on these factors this corpus can be considered to be representative of common engineering design scenarios.

3.1.1. Coding Scheme

The coding scheme adopted for this research was originally developed by Wasiak et al. (2008; 2010) to classify engineering email content. It was created from an extensive review of the literature on classifying information in various fields, including engineering design, sociology, and organisational behaviour. The categories comprehensively cover *How* the information is presented, *What* it is about (whether it is product or process-related), and *Why* it is being created (in terms of problem solving activities and intent of the communication). This existing classification scheme was used for the coding because of the relatively unknown nature of the information content. By not restricting the scheme to a particular aspect of the information content, it was considered that a richer picture of how logbooks support the creation of formal information could be gained. The detailed rationale for the selection of the terms is discussed by Wasiak et al. (2008, 2010) and the full coding scheme is presented in Table 3.

Table 3: Information Coding Scheme (*adapted from* Wasiak et al. (2008, 2010))

What			Why		How
Product	**Project**	**Organisation**	**Problem Solving**	**Communication**	**Information classes**
Functions Things the product must do, e.g. 'Be fast'	**Risk** Assessing likelihood and weighting implications	**Stake Holders** Shareholders, customers, directors and their culture and politics	**Goal Setting** Identifying where the design is, and to where it needs progressing	**Clarifying** Clearing up mis understandings (both requesting and in response).	**Written note**
Performance How well the product achieves its functions	**Planning** Management of phases, activities and tasks	**Economic Issues** Costs and efficiency, market and product selection	**Constraining** Imposing boundaries with requirements and desirables	**Debating** Discussing opposite views	**Meeting note**
Feature The quality or characteristic with which the function is achieved	**Team** Team selection and development	**Human Resources** People, availability, allocation, training etc.	**Solving** Encompasses one or more of the following stages: searching, gathering, creating and developing solutions	**Informing** Sharing, presenting or distribution information with others. No response is required. It is passive	**Sketch**
Operating Environment Objects that interact with the product	**Quality Management** Quality, standard or expectations	**Physical Resources** Ranging from offices to equipment	**Evaluating** Judging the quality, value and importance of something	**Exploring** Discussing possibilities and ideas, invoking suggestions	**Table of figures**
Materials Materials selection and characteristics	**Cost** Financial arrangements at the level of the project, rather than specific component costs	**Financial Resources** Cash, Assets, Borrowing	**Decision Making** Considering key factors from evaluation and possible compromises to form a decision	**Digressing** Discussing irrelevant material	**Calculation**
Manufacturing Consideration of manufacturing, assembly and transport	**Time** Timescales, deadlines	**Knowledge Resources** Current ability and stored information		**Managing** Includes arranging, directing and instructing. Implies action (such as a response) needs to be taken	**Contact Information**
Cost Consideration of costs particularly unit costs		**Tools and Methods** Specific testing and modelling techniques			**Graph/Chart**
Ergonomics User Interaction with product		**Practices and Procedures** Accumulated by the company,			**External Document**
					Annotated External
					CAD
					Annotated CAD
					Memorandums
					Completed Forms

		often developed through experience			

For the purposes of this research, two modifications were made. First, the analysis included the 13 information classes (written notes, meeting notes, calculations, sketches etc.) previously identified from logbooks by McAlpine et al. (2006). It was contended that being able to compare the type and proportion of classes of information in the logbooks and formal reports allowed greater insight to be drawn about how logbooks support the varied perspectives described in Section 1.2.

Second, the coding scheme originally included a 'communicative acts' category. This was intended to classify the type of communication act between people, and covered the way in which language was used in dialogue (e.g. the use of agreement or disagreement terms). It was thus not appropriate to include it for this research, where the communication was essentially one-way (team member to logbook or report) and not expressed in the form of dialogue that could be analysed in those terms.

All entries were coded with at least one term from each top-level category and all entries could be classified into one of the 13 previously identified information classes.

3.1.2. Coding Strategy

For the purposes of coding the documents, the information was split into appropriate 'chunks'. Logbooks were split into 'entries' (clearly defined chunks of information), usually separated by a terminating line, or the start of a new entry (McAlpine et al., 2006). The reports were split according to their numbered sub-sections. Although not perfectly analogous, report sub-sections do generally correspond to logbook entries, as they both deal with one aspect of the design or process. The unit of analysis was also selected as a best compromise between detail (granularity) and coding effect.

The reliability of the schema has been previously demonstrated on other documentation covering a variety of design project types (Wasiak et al., 2010). Although this assessment found levels of agreement between coders at the lower level did vary, there was "*near perfectly consistency*" between coders at the higher (product, project, organisation) categories. A further, larger study of an email corpus with the same classification schema also reported high reliability. As such, inter-coder reliability was not considered an issue during this analysis.

As well as the percentage of entries or report sections comprising the different information classes, the actual number of information objects (sketches, calculations, and CAD drawings) was also recorded. The results for the information content categories (product, project, organisation, and problem solving and communication activities) are presented as the percentage of entries that contain each category and sub-category. For example, if 50 of 100 logbook entries contained some aspects of product performance, the percentage of entries would be 50%. As entries can – and often did – contain multiple categories of information content, the presented percentages total more than 100%.

3.2. Results

This section presents selected results from the study comparing formal and informal documentation. Table 4 shows the key characteristics of the documents analysed, along with the number of instances of sketches, calculations and drawings.

Table 4: Key Characteristics of Dataset

	Logbooks	Reports
Number of logbooks/reports	6	11
Total page volume	540	375
Total Entries	372	405
Average length of entry (pages)	1.45	0.93
% of entries with 2+ info types	33%	18%
Average info types per entry	1.45	1.21
Number of Sketches	124	34
Number of Calculations	52	21
Number of CAD drawings	0	30

As expected, the logbooks contain many more sketches than the reports, and the reports contained many more formal representations in the form of CAD drawings. The differences in the distribution of information classes is illustrated in Figure 5[1].

It can be seen from Table 4 and Figure 5 that there is a complete absence of meeting notes in the reports (compared to over 20% of logbook entries being meeting notes). Other substantial differences can be seen in the number of sketches (which were often very quick and informal in nature) and amount of entries containing calculations. It was observed that tables of figures

[1] Where the information class was present in less than 5% of the entries, they have been grouped into 'all others' for clarity of presentation.

were used more often in the reports to summarise the results of calculations, and this is manifested in Figure 5. The 'richness' of the entries (i.e. how many types of representation they include) also differed significantly, with many more logbook entries containing two or more information classes (33% v. 18% for reports).

These observations support the concept of logbooks facilitating cognition and the creation of written output through, for example, meeting notes and sketches. The myriad types of entries also support the concept of logbooks as a means for gathering and collation of various types of information e.g. written notes, sketches, and external documents, relating to the high interconnectedness found in Study 1.

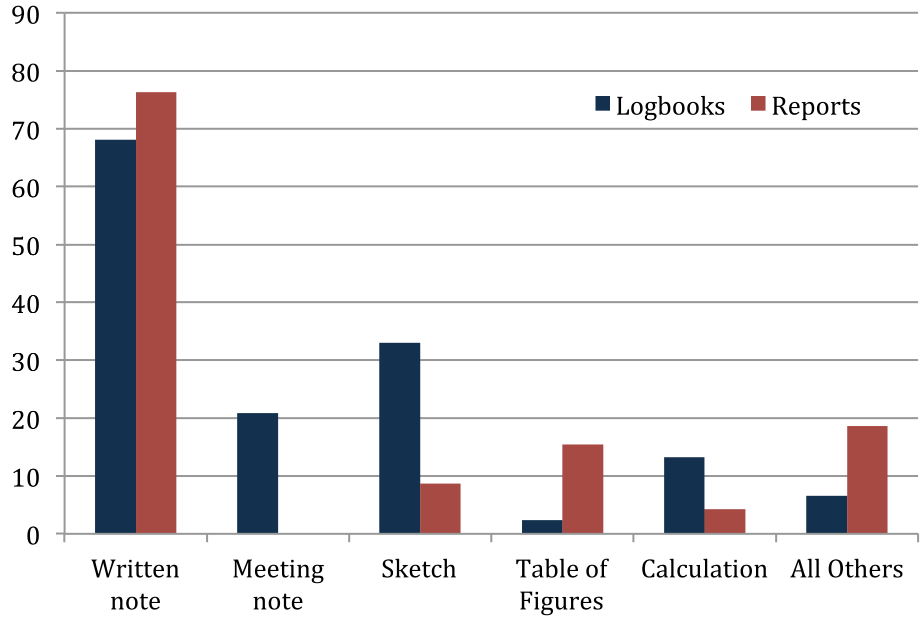


Figure 5: Percentage of entries containing various information classes

Considering *What* the entries are concerned with and *Why* they are created, Figure 6a shows the trends between the logbooks and reports to be remarkably similar, with the exception of the relative lack of project-related information in the reports: 55% of logbook entries contain some elements of project-related information v. just 15% of entries for reports.

Next, consider the lower level categories of 'Project', 'Problem Solving', and 'Communication' in detail. Project-related information covers topics associated with managing risk, planning/task allocation, and timescales. The breakdown of the project category in Figure 6b reveals more detail about the large differences in the number of project-related entries mentioned previously. It can be seen that most of the difference arises from the relative absence of 'planning', 'team', and 'time' entries in the reports, with, for example, nearly 50%

of logbook entries containing some elements of planning, compared to only around 7% of report entries. These differences can be attributed to i) a significant amount of planning and task allocation (referring to team members) being recorded in meeting notes, which were completely absent from the reports (20% v. 0%); ii) logbooks were all chronological and often resembled a diary with the logbook acting as a living document, making planning an integral and natural part of many entries; and iii) logbooks were frequently used to track tasks outstanding for the individual in 'to-do' style lists at the beginning of entries. These features again link to the concept of logbooks facilitating cognition and the creation of written output.

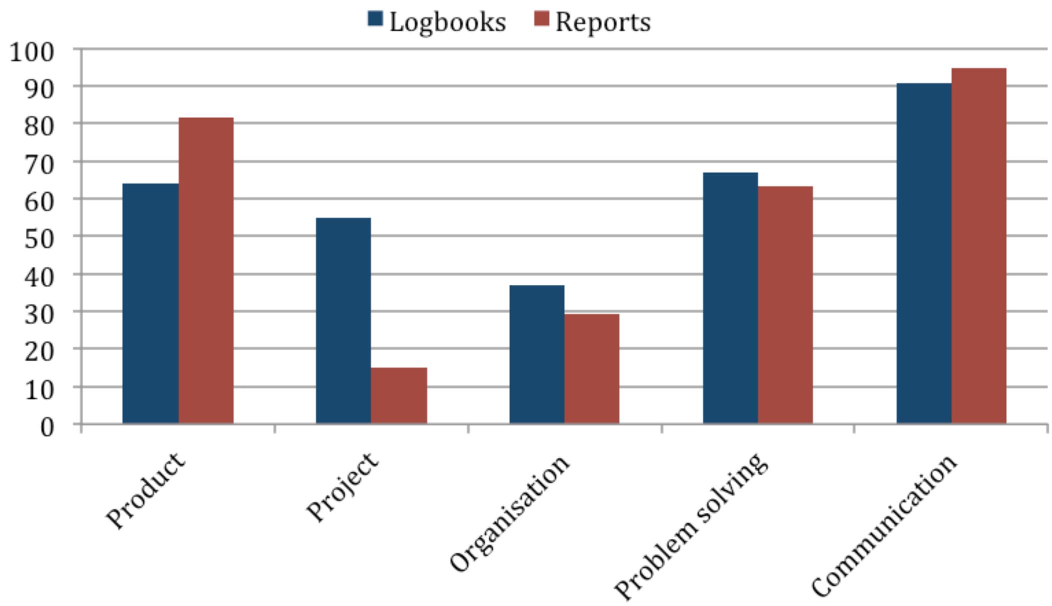


Figure 6a: Percentage of entries containing high level categories

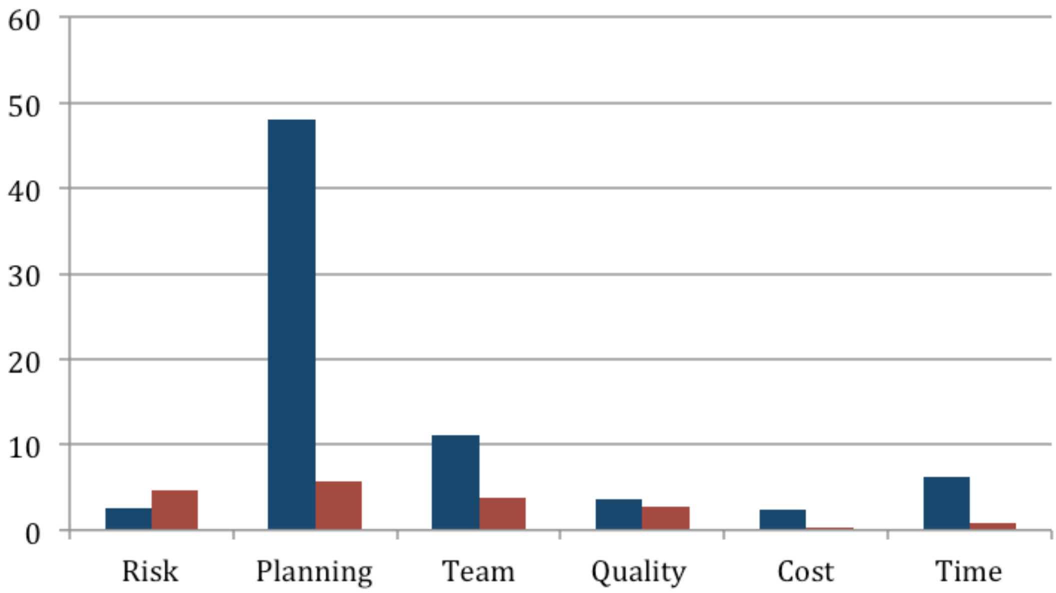


Figure 6b: Percentage of entries containing low level categories of project information

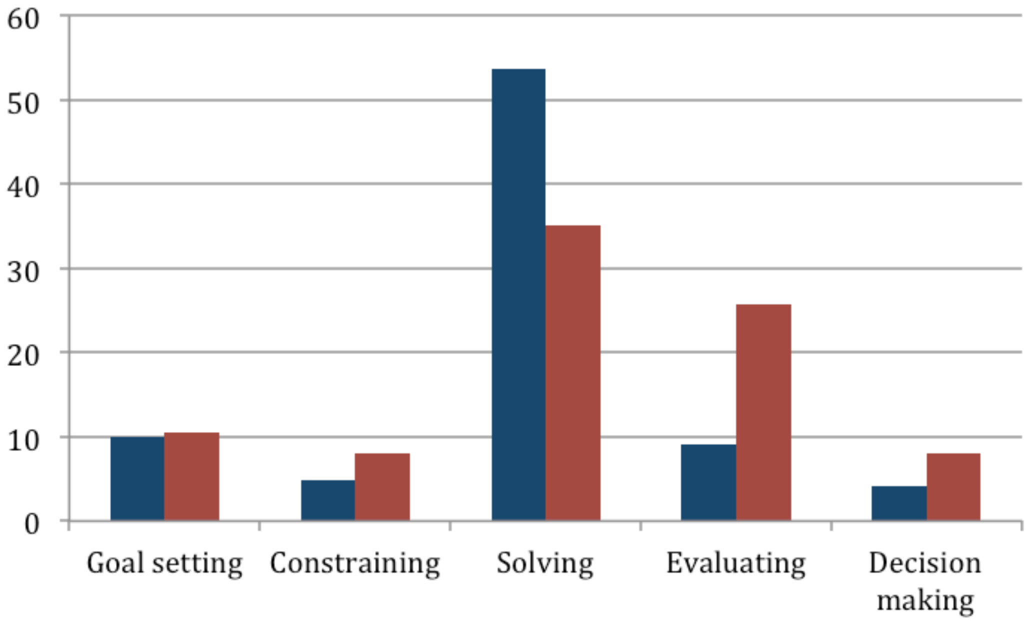


Figure 6c: Percentage of entries containing low level categories of problem solving information

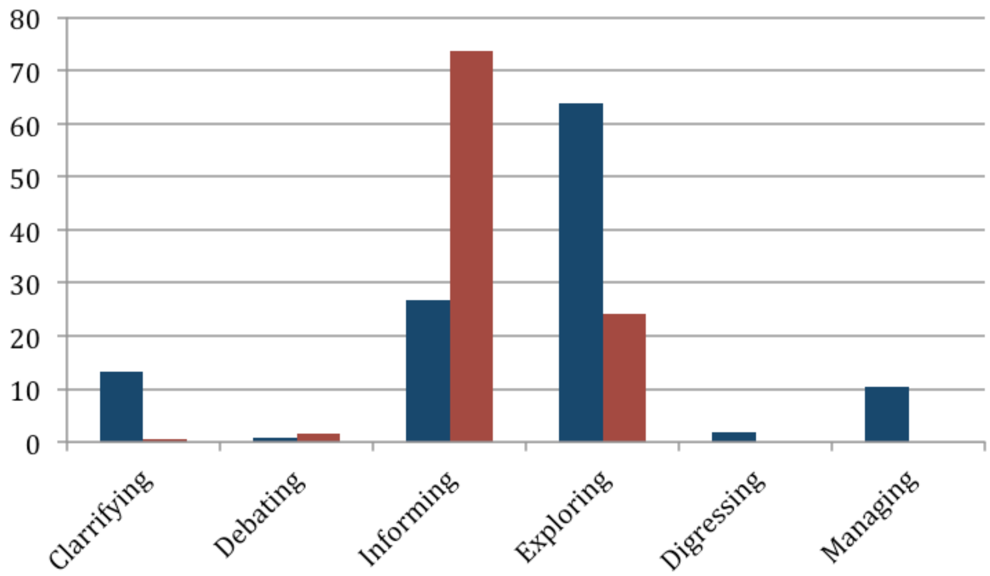
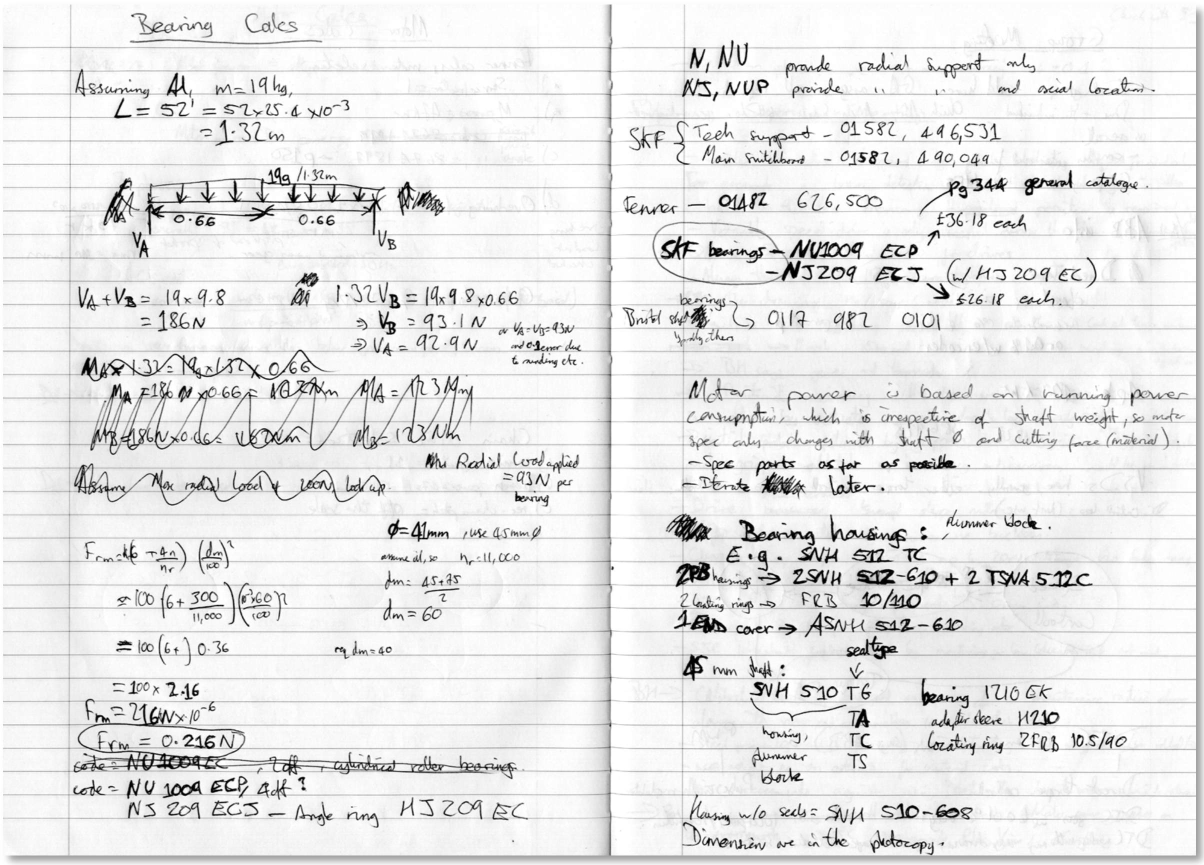


Figure 6d: Percentage of entries containing low level categories of communication information

Moving to the low level problem solving categories (Figure 6c) it can be seen that entries containing 'goal setting' and 'constraining' activities are at broadly similar levels. However, there are significant differences between the amount of entries containing 'solving' and ‘evaluating’. The large percentage of entries containing elements of solving (searching for, gathering and developing solutions) links to the logbook as a facilitator between cognition and output from a different perspective – helping engineers to structure problems and work through possible solutions.

The overall percentage of entries containing high level ‘communication activity’ (Figure 6a) was, unsurprisingly, almost 100%. This is simply because virtually all entries can be classified as communicating *something*. However, observing the low-level communication categories reveals that the nature of this communication differs significantly between logbooks and reports. This is shown in Figure 6d. The main difference here is the contrast between entries that are informative in nature (27% for logbooks v. 74% for reports) and those that are exploratory, where the trend is almost exactly reversed (64% for logbooks v. 24% for reports). ‘Informative’ in this context means that the entry states one position, and does not consider options, alternatives or the rationale for the statement, whereas ‘exploratory’ entries do consider alternatives. This difference is a demonstration of staging prior to transformation of informal information to formal information.

Two examples can be used to further illustrate apparently fundamental aspects of logbook use derived from this study. The first example in Figure 7 shows a logbook entry concerning the specification of bearings on a shaft, and the corresponding section in the final report. Here the interwoven nature of logbook entries can be seen, with text, calculations, cost information, contact details, and sketches all present. This illustrates how logbooks support the gathering and synthesis of thoughts and ideas, as well as information from various sources. In contrast, the corresponding report entries are generally textual and presented in a factual manner. Whilst this characteristic can make the content easier to follow than the relatively ‘messy’ logbook entry, no alternatives are offered, no calculations are shown, and the rationale for the assumptions made for the analysis are not apparent – it is a tidy, ‘sanitised’ version of the relatively messy process of design.



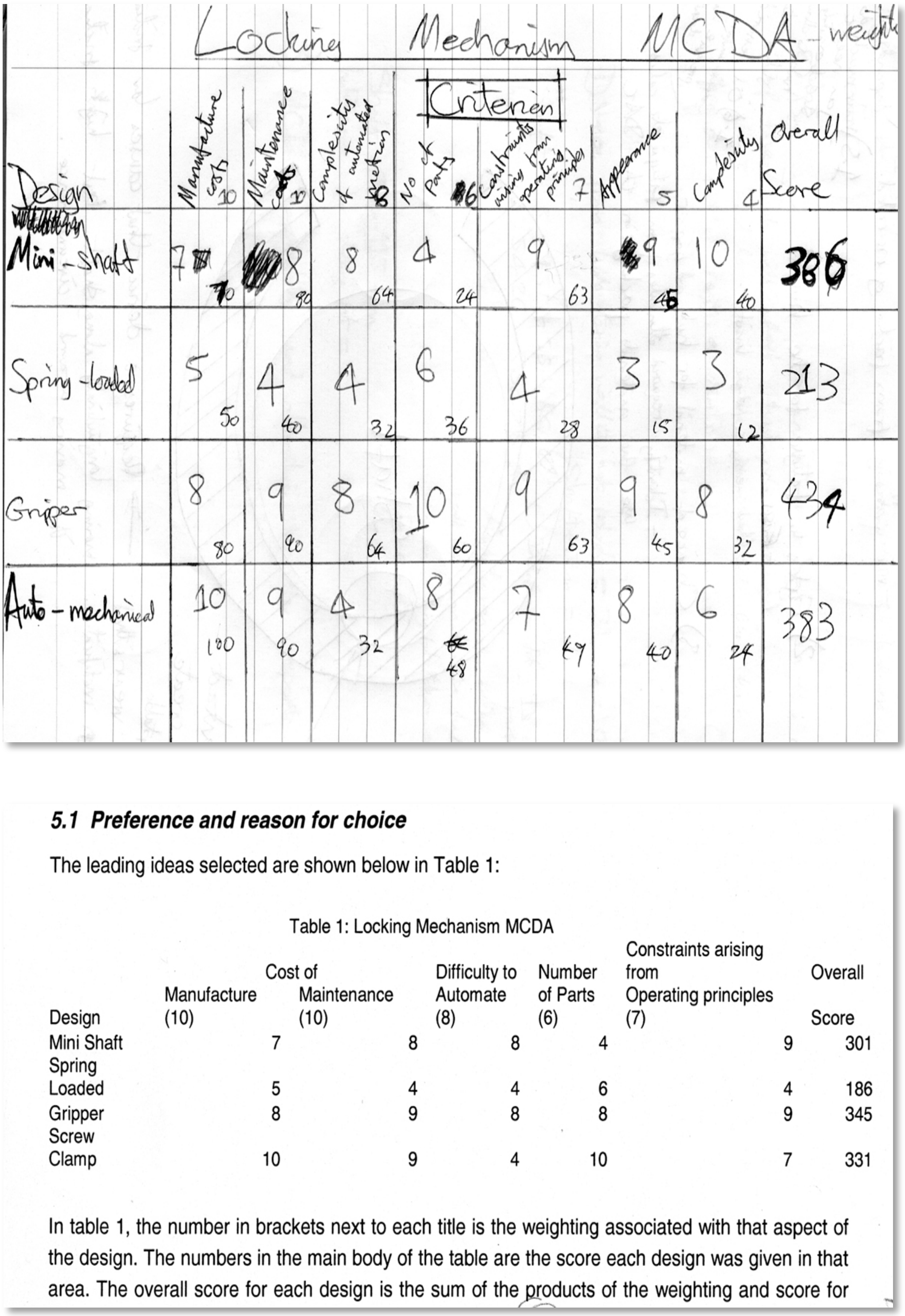
6.2.4 Bearing Specification

The bearings will not experience any significant axial load. The load will be mainly radial. The most suitable bearings for the task were cylindrical roller bearings. The design chart in appendix section 12.8 shows the relative strengths and weaknesses of the most common types of bearing. It is clear from the table that cylindrical bearings are the most suitable. All bearings were selected from the SKF range, and one NU1009ECP (providing radial location of the shaft) and one NJ209 ECJ (providing radial and axial location) are required for each shaft. Adaptor sleeve HJ209 and locating ring 2FRB 10.5/90 are also required for each shaft. The housings selected were SNH 510-608.

Figure 7: Example of difference in nature of corresponding entries

A second excerpt from a logbook entry is given in Figure 8, along with its corresponding reporting section that details the output of a multi-criteria decision analysis (MCDA). This is a weighted table that is designed to compare various criteria in order to select one from a number of alternative locking mechanism designs.

While it can be seen that in both cases, the 'Gripper Screw' design achieves the highest overall rating, the numbers differ (434 vs. 345 in the formal report). This is due to the 'Appearance' and 'Complexity' categories being omitted from the table in the final report, as well as a transcription error.



Locking Mechanism MCDA - weights

Criterion

Design	Manufacture costs 10	Maintenance costs 10	Complexity of automated function 8	No of Parts 6	Constraints arising from operating principles 7	Appearance 5	Complexity 4	Overall Score
Mini-Shaft	7 / 70	8 / 80	8 / 64	4 / 24	9 / 63	9 / 45	10 / 40	386
Spring-loaded	5 / 50	4 / 40	4 / 32	6 / 36	4 / 28	3 / 15	3 / 12	213
Gripper	8 / 80	9 / 90	8 / 64	10 / 60	9 / 63	9 / 45	8 / 32	434
Auto-mechanical	10 / 100	9 / 90	4 / 32	8 / 48	7 / 49	8 / 40	6 / 24	383

5.1 Preference and reason for choice

The leading ideas selected are shown below in Table 1:

Table 1: Locking Mechanism MCDA

Design	Cost of Manufacture (10)	Cost of Maintenance (10)	Difficulty to Automate (8)	Number of Parts (6)	Constraints arising from Operating principles (7)	Overall Score
Mini Shaft	7	8	8	4	9	301
Spring Loaded	5	4	4	6	4	186
Gripper	8	9	8	8	9	345
Screw Clamp	10	9	4	10	7	331

In table 1, the number in brackets next to each title is the weighting associated with that aspect of the design. The numbers in the main body of the table are the score each design was given in that area. The overall score for each design is the sum of the products of the weighting and score for

Figure 8: Example of discrepancies in corresponding entries

These two examples serve to illustrate aspects of logbook use that bring together perspectives from Section 1.2. Firstly, they show that logbooks are used to gather and integrate data and information from various sources. Secondly, they show that information may be reflected upon, iterated, and finally transferred into a formal report i.e. transformation of informal information into formal information.

4. Discussion

The studies first reveal the central position and highly interconnected nature of logbooks, which act as a 'hub' through which ideas and information are collated and synthesised. Further, the results show the emergence of design in logbook records, in comparison to formal records, as manifested by logbook entries containing elements of 'solving' and 'exploring'. Logbooks are also richer in terms of the types of information, the amount of rationale, and especially the amount of project and process-related entries. In contrast, reports – as one might expect – place more emphasis on evaluating the performance of the final product/artefact, largely through qualitative, textual description, tables summarising information, and CAD drawings. Together these results, and in particular those from Study 1, answer the first question outlined in Section 1.2: *how do logbooks fit into the wider landscape of PIM*? Specifically, logbooks occupy a space distinct from other PIM tools, in terms of use, connectivity, and centrality.

Next consider the second question from Section 1.2: *how can the varied descriptions of the mechanisms underpinning logbook use be reconciled in a single coherent framework*? We propose that the fragmented perspectives found in Section 1.2 can be dissolved by characterising logbooks as multi-modal mediators of information; where to mediate is to "*occupy an intermediate or middle position or form a connecting link or stage between two others*" (Oxford, 2010). The concept of artefacts 'mediating' human activity is not a new one, first being discussed by Heidegger in 1927 (Heidegger & Krell, 1993), and more recently by Boujut and Blanco (2003) who argue that mediators are not limited to sketches, or Information Technology artefacts, but any artefact that acts as a "*mediator in the building of shared understanding.*" Building on the definition by Boujut and Blanco (2003), the perspectives outlined in Table 1, and the empirical results, we propose that the engineers' logbook acts as a mediator in the following three ways:

Mode 1 As a means of *facilitating cognition and the creation* of written output i.e. supporting the reflective practice of the engineer in the form of sketches and notes.

Mode 2 As a means of *gathering and collating* information from different sources and of different types i.e. as a 'cache' for many different types of information to be collated, interpreted and synthesised.

Mode 3 As a means of *staging* information prior to *transformation* from informal to formal information i.e. as a conduit for information rationalisation and structuring.

Decomposing this multi-modal description, aspects of each mode have previously been recognised as independently important to supporting engineering design work. For example, Currano & Leifer (2009) and Oehlberg et al.'s (2009) work link to the reflective cognition mode (1), Fredian & Stillerman's (2006) to the collation mode (2), and Boujut and Blanco's (2003) to the staging mode (3). Thus each mode captures one of the common elements linking perspectives on the role of logbooks e.g. as facilitators of cognition and creation through reflective practice (Schön & Wiggins, 1992). Further, by considering the modes as being supported simultaneously it is possible to dissolve many of the conflicts highlighted in Section 1.2. For example, Modes 2 and 3 together encapsulate the repository type perspective articulated by e.g. Yang et al. (2005); while Modes 1 and 2 together describe the externalised memory type perspective described by e.g. Schraefel et al. (2004). Thus, the findings from this work point to a more complex conceptualisation of the mechanisms underpinning logbook use, where the three mediation modes are simultaneously supported. This is illustrated by the multitude of information transformations found in Study 1, and the large number, and extent, of activity types described in Study 2. In particular, it is the requirement for simultaneous support for these three modes that points to the limitation of past mono-modal descriptions, and differentiates logbooks from the other PIM tools evaluated in Study 1.

Table 5 illustrates the three modes of mediation, as evidenced in this research. The extent of the modes is detailed explicitly by the quantitative assessment of their presence in the dataset. For example, one element that demonstrates the existence of Mode 1 mediation is problem-solving activity in logbooks. The extent of this first mode is then summarised with respect to the study data e.g. 67% of entries in Study 2 relate to problem solving activity (Figure 6a). As such, Table 5 supports both the existence of the three modes, and our claim that they are extensive.

Table 5: Manifestations of Modes of Mediation

Mode of Mediation	*Evidenced by*
Mode 1: Facilitating cognition and creation	• High levels of problem solving (67% of entries, Figure 6a) e.g. clarifying and evaluating. • High levels of exploring (64% of entries, Figure 6d) e.g. rationale given, alternatives considered. • Iteration and refinement of ideas e.g. correcting mistakes (Figure 7). • A large number of sketches and other reflective activity (33% of entries, Figure 5). • Numerous notes to support interpretation or memory e.g. to-do lists, meeting notes and notes about the project, planning, team and time (68% of entries contain written notes, Figure 5)
Mode 2: Gathering and collation	• High levels of mixed media entries (57 links to informal information, 92 links to formal information) e.g. combining two or more info types. • Annotation of other information types (68% of entries contain written notes, Figure 5, coupled with the high number of links) • Highly connected to other tools and information sources (139 links to other information sources).
Mode 3: Staging and transformation	• High number of connections to formal sources (92 links to formal sources). • Acting as conduit i.e. providing a conduit for the synthesis of multiple informal sources into a smaller number of formal documents (linking to both informal and formal). • Rationalisation and reduction of concepts to neat 'sanitised' forms (Figure 8).

4.1. Logbooks in Support of Mediation

Previous works have proposed various reasons for the assumed dominance of paper logbooks in the workplace. A significant portion of these have focused on the affordances of logbooks as a paper medium e.g. low cost, ease of access, and non-linear interaction (Liang et al., 1998; Wilcox et al., 1997). In particular, projects have sought to produce digital alternatives that replicate the logbook's 'surface' functionality such as the tagging of information (Fredian & Stillerman, 2006) or the medium of the logbook itself (Oehlberg et al., 2009). A recurring criticism of these approaches in the engineering domain is that they do not account for the key cognitive support provided by logbooks in the form of mediation (Currano & Leifer, 2009; Hicks et al., 2002). In this context, mediation has, to date, typically been described as from a single perspective e.g. supporting reflective practice (Valkenburg & Dorst, 1998).

This research both validates previous studies' assumptions about the centrality (Study 1) and possible roles of logbooks (Study 2), we well as highlighting a key limitation of past conceptualisations of the role of the logbook in engineering work. Here, Study 1 details the manifestly dominant, central position of logbooks, connecting other information sources, with 139 links (Oehlberg et al., 2009; Sobek, 2002). Further, the overall results highlight the unique role of logbooks in bridging various media (with connections between various information sources), and supporting iterative work, where problem solving (67% of entries), exploring (64% of entries), and refinement are dominant (Currano & Leifer, 2009). However, a key finding not previously described is that many of the logbook entries examined in Study 2 served multiple roles (e.g. planning, solving and exploring are present in circa 50% of entries) that link to both media focused and mediation focused prior works.

For example, the fact that the paperless office has still not arrived is often greeted with surprise due the development of digital tools that each better support specific aspects of engineering work (York, 2006). However, the multi-modal perspective proposed here resolves this paradox, as well as the conflicting perspectives highlighted in Section 1.2. Although some tools may better support individual activities, no single tool effectively supports the three modes simultaneously and are thus unable to compete with the multi-modality and affordances of the paper logbook. This conclusion is reinforced by the results presented in Figure 4, where logbooks are connected to multiple document types via various modes. In contrast, all other tools are only strongly linked to a one or two different document types via mono-modal connections. This mono-modality is often self evident in PIM tools. For example, Word provides a poor platform for reflective sketching despite the possibility of creating figures. This immediate and flexible multi-modal support logically fits the dynamic, iterative nature of engineering design work (Dorst & Cross, 2001), as well as the behaviour underpinning designers interaction with information (Robinson, 2010). Ultimately these findings link to wider concepts of human work where multiple cognitive processes interact in a complex weave of activity (Cash, Hicks, & Culley, 2015), and dynamically influence each other as well as reacting to the physical world (Pinker, 1999).

Exploring this simultaneous support concept further we contend it is the synthesis of mediation modes and pragmatic factors that cement logbooks at the core of engineering design work as illustrated in Figure 9. However, this suggests two key areas for further investigation. First, it is unlikely the three identified modes describe a comprehensive list of all possible modes across all available PIM tools. Indeed it is likely that some tools have unique modes or otherwise unique mode combinations that let them excel at particular aspects of information work. This is supported by the fact that numerous PIM tools are similarly heavily used but less interconnected in comparison to logbooks (Study 1). Further work is required to investigate the existence of additional possible modes and their interrelationships, thus extending the current framework (Figure 9) to better encapsulate the whole range of PIM tools. Second, it is likely that modes are scalar i.e. email might support Mode 2 to a greater degree than that provided by logbooks. This could also apply to mode combinations e.g. post-its might support all three modes but to differing degrees from that associated with logbooks.

Further work is thus required to understand which modes are supported, to what extent, and in what combination across the PIM landscape.

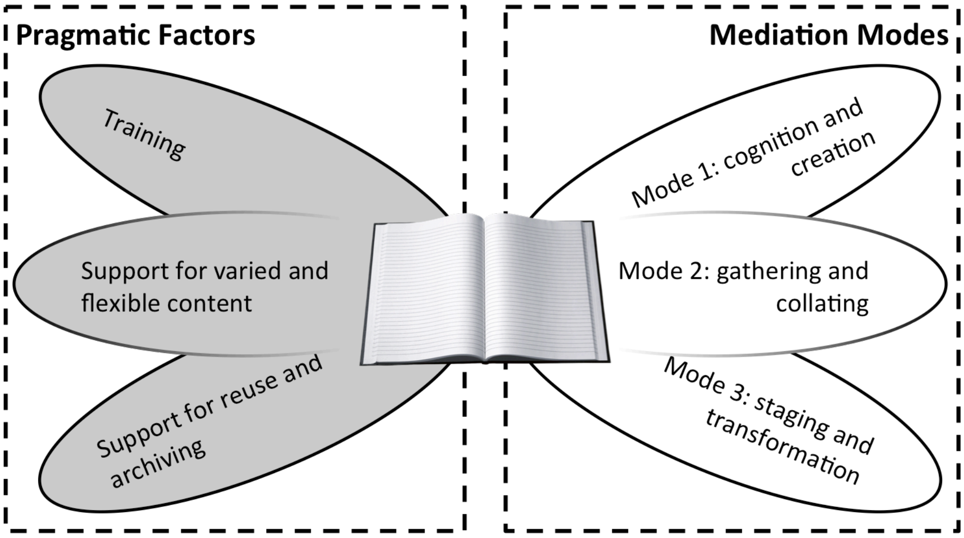


Figure 9: Logbooks at the intersection of pragmatic factors and the three mediation modes

4.2. Implications for Supporting Engineering Work

As previously stated, we contend that the reason informal, often paper-based tools are so enduring (cf. the myth of paperless office) is because they simultaneously link the three modes of mediation and the three pragmatic factors described in Section 1 (Figure 9). This is in contrast to almost all other engineering design tools, which tend to focus on supporting only one type of mediation. Building on this we propose a number of practical implications for both researchers and practitioners seeking to support engineering design work.

1. Quick recording/collection of mixed-media notes

Previous work has highlighted the variety of information typically contained within logbooks (McAlpine et al., 2006; Sobek, 2002), which is further supported in this paper. It is argued that a quick method to record the myriad types of information encountered by engineers during the course of their work is essential to support the logbook's role in mediating cognition/memory and output. Particularly important for this is the ability to support free-form entry, including writing, sketching, and annotation. This must also be compatible with the large number of other information sources to which logbooks are linked.

2. Synthesis of mixed-media notes

Study 1, in particular, highlights that logbooks are used to collect and synthesise many types of information in many different forms. It is contended that in their present form logbooks do not optimally support this activity. Hence improved support and in particular being able to synthesise information from both paper and digital resources is key to the success of future support strategies, whether paper-based or electronic.

3. Better support for information transformation

The third mode of mediation is perhaps the least well supported by current paper logbooks, with information invariably having to be re-produced in the formal document (for example, transforming sketches to CAD, re-creating calculations in analysis software, or re-typing meeting notes into a word processor). Whilst this re-creation process often allows the engineer to 'tidy up' the relatively 'messy' informal information, the disconnect between the logbook and the almost exclusively digital tools used to create the formal project record (Figure 2) lead to two potential problems: i) loss of important rationale and other contextual information (Figure 7); and ii) opportunities for errors when transferring the information from one form to another (Figure 8).

4. Better support for linking information

Connected to the issues of poor support for transforming information is the need to support more explicit links between logbook information and its formal counterpart. Previous work has shown that browsing through pages, and relying on memory are the predominant ways of re-finding information in paper-based logbooks (McAlpine et al., 2006). While this approach might be appropriate for an individual, it clearly does not scale well, or afford opportunities for re-use by anyone other than the original author. Furthermore, the facility to create more explicit and persistent links between logbook information would arguably allow more effective traceability for audit, intellectual property, and design re-use by allowing access to the rich rationale and contextual information that logbooks often contain.

4.3. Limitations

Based on the study method there are a number of limitations. First, the participants chosen for the studies included both practitioners (Study 1) and trainee engineers (Study 2). Although this introduces some differences within the population, this is mitigated by the fact that they both use logbooks in similar ways – reinforcing each other. In particular, the fact that both studies corroborate the findings suggests that the mediating roles are generalizable across experiential boundaries. This is further supported by the spread of background characteristics in the practitioner population (Study 1), where again, despite differences, the results are consistent across the population.

Second, the intra-record audit was conducted without comment from the participants. In mitigation of this, the coding schema is both well established and previously validated (Wasiak et al. 2010). Further, the alignment between the two study elements reported here, and other works using logbook analysis in other contexts provides additional confidence in this method.

Finally, the complexity of the relationships between the mediating logbooks and the other PIM tools provides significant scope for further research. In particular, how changes to the mediator e.g. changing the logbook medium, propagate out to effect other PIM tools is currently not well understood and represents an important next step.

5. Conclusions

This paper has reported two complementary studies, which collectively address the two research needs: to investigate how logbooks fit into the wider landscape of personal information management; and to explore how the varied mechanisms underpinning logbook use can be reconciled in a singly coherent framework. Study 1 explicitly confirmed and detailed the unique position of logbooks in terms of use, connectedness, and centrality within the PIM landscape. Study 2 then explored the specific mechanisms underpinning the affordances of logbooks in the engineering design context. These collectively contribute to design information management research, and in particular reveal how logbooks simultaneously fulfil three key mediation roles. This expands the conception of engineering work as a purely information transformation process. Further, this brings together previous research where various perspectives on logbook use have been explored in isolation. For example, reflective sketching and the importance of external mediators in design thinking has been highlighted by Valkenburg & Dorst (1998). This work has revealed the key role logbooks play via Modes 1, 2, and 3, acting as a means of: facilitating cognition and creation, gathering and collation of information, and staging of information prior to transformation between informal and formal information. In this context, engineers' logbooks provide an almost unique source of insight into the interaction between the engineer and the information (types and sources) involved in engineering design work, with logbooks linking to over 130 other information sources.

The multi-modal mediating role of logbooks provides a new perspective on how engineers work with, and utilise information. This multi-modal conceptualisation also helps to explain previous failed attempts to digitally replicate logbooks or offer alternative PIM tools. Further, by confirming and detailing the interconnection between logbooks and other PIM tools this research validates, connects, and extends many previously disparate design information management studies, which have focused on individual tools. Thus, these findings have significant implications for both how engineers use information and logbooks (or other mediators) to manage their design work, as well as for researchers seeking to understand engineering information processes. In particular three areas for further work are proposed. First, in mapping the influences between the mediating object and the other information elements encountered, and what implications this might have as researchers and practitioners seek to replace physical logbooks in the future. Second, mapping the range of modes extant in the wider PIM landscape. Third, investigating how these combine and to what extent they manifest across the PIM landscape. It is vital therefore that when considering how best to support engineering design work, one should not seek to reproduce the 'surface' functionality of logbooks or other mediating objects, but instead seek to ensure that the simultaneous modes of mediation, and interconnection between tools identified in this paper are adequately afforded.

Acknowledgements

The work reported in this paper has been undertaken as part of the Language of Collaborative Manufacturing Project at the Universities of Bristol and Bath, and which is funded by the Engineering and Physical Sciences Research Council (EPSRC), grant reference EP/K014196/2. Supporting data are openly available at 10.5523/bris.16zg08ape366i1wka7ziwbl0p8

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