NordDesign 2006
August 16 – 18, 2006
Reykjavik, Iceland

Evaluation of DRed a way of capturing and structuring engineering processes

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Abstract
This paper describes research that was carried out in collaboration with the aerospace group of a major power systems company to evaluate a software tool called DRed that allows engineering designers to document their design rationales. DRed is one of many proposed derivatives of the IBIS concept. DRed allows the issues addressed, answers considered, and associated arguments, both for and against, to be captured graphically. The paper presents an analysis of DRed issues to understand the nature of the questions documented by engineering designers. The frequency of use of pairs of DRed elements is also analysed to understand how engineering designers developed DRed structures. The paper finally compares the design information captured in DRed design folders with that captured in Design Definitions Reports (DDRs) to show how the use of DRed improves the richness of the recorded information.

Keywords: Design rationale, aerospace design, IBIS, knowledge representation, engineering knowledge management

Introduction
Aerospace engineering design relies heavily on the use of past experience [1]. It is known that engineering designers frequently need to revisit previous design solutions and understand the rationale for their generation [2]. A new IBIS-based software tool called DRed (Design Rationale editor) has recently been developed by researchers at Cambridge Engineering Design Centre (EDC) [3]. DRed allows designers to record their design rationale (DR) at the time of its generation and deliberation. The design rationale is displayed in a *document* as a graph of nodes linked with directed arcs. The user creates the nodes by choosing from a predefined set of element types. The key element types are: *issue*, *answer*, and *argument*. The software is already in regular use in design projects in an international aerospace company. A preliminary evaluation conducted in industry using questionnaires and telephone interviews with designers indicated that DRed is easy and intuitive to use and helps designers to structure their engineering process [4]. However, a rigorous and empirical evaluation of how DRed allows the capture, storage and retrieval of design rationale is still required. A project is therefore being carried out in collaboration with the industrial partner.

Research aims

The aims of this project are to determine if DRed: (1) improves the richness and clarity of the recorded information; and (2) has a beneficial effect on the design behaviour by prompting design thinking and helping designers to view their design process. This paper presents research to determine if DRed improves the richness of the recorded information. In order to address this research aim, five specific objectives were established. These objectives were phrased in the form of the following research questions:

- Do designers use DRed *issues* as instructed in the working practice guideline?
- What problem types do designers address through the *questions* captured in DRed?
- What *question* types do designers capture in DRed?
- Do designers use DRed *syntax* as instructed in the working practice guideline?
- Are more *answers per issue* and *arguments per answer* captured using DRed rather than textual descriptions?

The Dred tool

DRed is a simple software tool that is intended to be complementary to, and used together with, designers' standard analysis, CAD, office and web applications. It facilitates the creation of a *design folder*, storing all the electronic information generated during a design project that is structured according to the dependencies inherent in the design rationale. On completion of the project the folder can easily be published on-line using a conventional web server, for future reference within the company.

Research and implementation of DRed

The research and implementation of DRed were supported by the use of the software application Graphlet. This is a general purpose interactive tool for creating and manipulating node-arc graphs. The first prototype tool was realised after one month of software development. An efficient and productive research cycle of idea generation, implementation and testing ensued. Seven further releases, of steadily increasing capability and refinement, followed over the next eight months.

The DRed design folder

As a design proceeds, the *design folder* for the project provides a place where the team can store the emerging product definition, the ideas evaluated and accepted or rejected, clear rationale for these decisions, and all supporting documents. In its implementation, a DRed design folder is simply a directory, either personal or shared, containing at least a single DRed *document*.

Workplanes

The heart of DRed is the workplane, displaying a graph of nodes linked with directed arcs, which takes the place of pages in traditional designers' notebooks and formal design reports, see Figure 1. A typical design folder will contain many workplanes, each one consisting of a single DRed *document*. Workplanes appear as zoomable, scrollable, two-dimensional surfaces of unlimited extent scrolling rightwards and downwards. DRed elements (nodes) are normally created, positioned and linked manually by the user. The user chooses elements from a predefined set of types including the *issue*, *answer*, *pro* and *con argument*, see Figure 1. Any element on a workplane can be linked without restriction to any other, and any element can easily be converted from its existing type to another. Each element type has a predefined set of statuses, signified by changes in colour and geometry of the background shape or font style of the text. There is only a single type of link, a unidirectional arrow, which represents a dependency of some sort. The precise meaning of that dependency is inferred from the types of the elements at each end of the arrow.

Tunnelling links

Dependencies between elements that belong to different workplanes, may be made via tunnelling links. These appear to tunnel into the workplane and reappear at their destination element. The tunnel entrance and exit mouths are shown as small circular icons, which are always created as a pair, see Figure 1. Such links permit the rationale for larger design projects to be distributed across multiple workplanes, and laid out legibly while facilitating navigation between them.

The issue, answer, pro and con argument element types

These are the IBIS element types that allow designers to record and present their rationale [5, 6]. Unlike other IBIS systems, all of these element types have status information indicating the designer's considered view of them. This gives a clear view of the progress of the design and allows the knock on effects of revoked decisions, or the discovery of new information, to be propagated through the rationale.

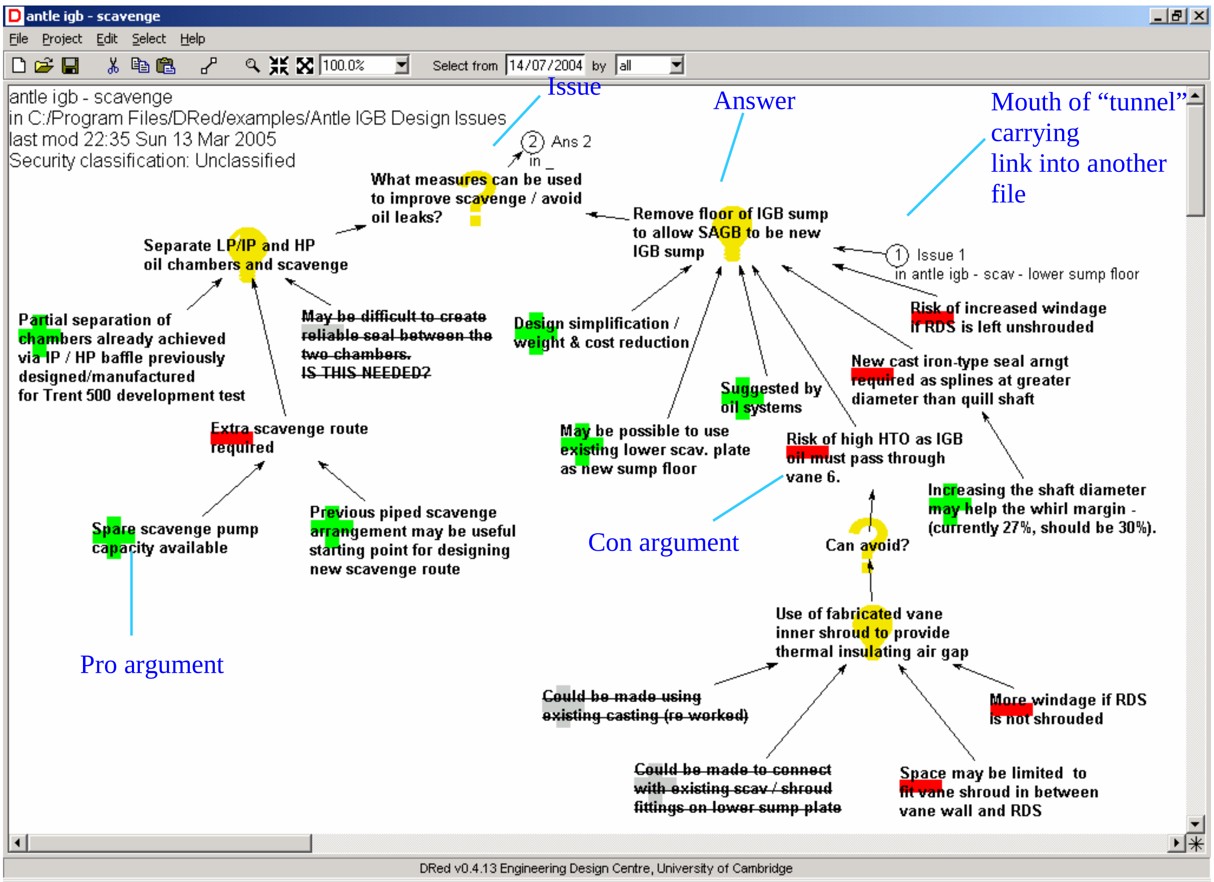

Figure 1. An example of DRed document capturing the design of an aero-engine internal gearbox

Research method

The research started by analysing a data set of DRed design folders with the aim of understanding if DRed issues were used as instructed by the working practice guideline. DRed working practice states that the issue elements should be questions. Preliminary data analysis showed that the issue elements were phrased both in the form of questions and considerations. Category A in Table 1 was developed to distinguish the issue elements depending on their *nature*. This category includes two types, namely *question* (A1) and *consideration* (A2).

Table 1. A: Nature category

Type	**Description**
1 Question	Interrogative sentence expressing an inquiry for information
2 Consideration	Statement indicating a need for information

Despite the structural difference of these two types, it was found that the considerations could always be rephrased into questions. Questions were found to be significantly more frequent than considerations. Although this finding was considered to be encouraging, it still did not help to understand the characteristics of questions. Previous research in engineering design indicated that the questions formed when designing along with their contexts can be used to describe engineering processes [7]. The questions were therefore analysed using two further categories. Category B in Table 2 distinguishes a question depending on the *problem* being addressed by a designer. This category includes three types, namely *diagnosis* (B1), *design* (B2) and *process* (B3).

Table 2. B: Problem category

Type	**Description**
1 Diagnosis	The question wants to develop the process to generate a cause to an undesired behaviour in a product
2 Design	The question wants to develop the process to generate a product form from an intended behaviour and other requirements
3 Process	The question wants to develop the process to generate a procedure

Category C in Table 3 distinguishes a question depending on the *objective* that a designer pursues when designing. This category includes seven types, namely *information* (C1), *confirmation* (C2), *comparison* (C3), *constructive generation* (C4), *explanatory generation* (C5), *analysis* (C6), and *evaluation* (C7). The objectives from C4 to C7, compared to those from C1 to C3, operate at a higher level of design thinking and enable designers to develop new problem solutions as well as revisit existing ones. This category was developed during an empirical study to characterise in detail the questions of engineering designers [8].

Table 3. C: Objective category

Type	**Description**
1 Information	The question wants to obtain information but does not indicate an objective
2 Confirmation	The question wants to establish the truth of a fact, the occurrence of an event or the existence of a state
3 Comparison	The question wants to establish similarities or differences
4 Constructive generation	The question wants to generate a solution: from the generation of creative conceptual solutions to that of detailed features of solutions
5 Explanatory generation	The question wants to generate an explanation: from the generation of explanatory conceptual solution to that of detailed features of solutions
6 Analysis	The question wants to establish the consequences of a solution by carrying out simulation and calculation
7 Evaluation	The question wants to establish whether a solution is satisfactory or not and in the affirmative case the degree of merit by comparing its consequences with the requirements and other criteria

After the investigation of the issue elements, the data set of DRed design folders was analysed with the aim of understanding if DRed syntax was used as instructed by the working practice guideline. DRed working practice specifies valid and invalid link types for pairs and trios of elements. Table 4 presents nine link types for pairs of elements. Note that *link type* 9 is invalid when DRed is used to support design tasks, but it is valid when it is used to support diagnosis tasks. The frequency with which the nine link types were used was counted and considerations were made with regards to the use of DRed.

Table 4. DRed link types

	VALID LINK types
1	I ß I
2	I ß A
3	A ß AR
4	A ß I
5	AR ß I
6	I ß AR
7	AR ß AR
8	AR ß A
	INVALID LINK type
9	A ß A
I: issue; A: answer; and AR: argument	

After the investigation of DRed link types, further research was undertaken to determine if DRed improves the richness of the recorded information. A simple method of evaluating this claim was identified and consisted of comparing the information recorded in four DRed design folders to that in four Design Definition Reports (DDRs).

The DDRs are generally structured in three main sections as follows: (1) problem diagnosis; (2) alternative solutions description; and (3) final solution description. The DDRs in the data set used in this project are in the form of plain textual descriptions. These reports were generated before the introduction of the DRed tool in the collaborating company. In addition, the reports were produced at the end of different design tasks to capture the rationale behind the development of specific design solutions. It is noteworthy that this type of design rationale capture is retrospective. At the time of their creation, the DDRs represented the only formal means of documenting design rationale.

The use of DRed shifted the *design rationale capture* strategy of the collaborating company from retrospective to real time, see Figure 2. The new strategy contributed to making available structured design rationale that was captured during the design process using DRed. This situation led to the idea to automatically extract DDRs from DRed design folders. In order to compare DRed design folders to DDRs produced before the use of DRed, the latter were reversed engineered into DRed, see Figure 2.

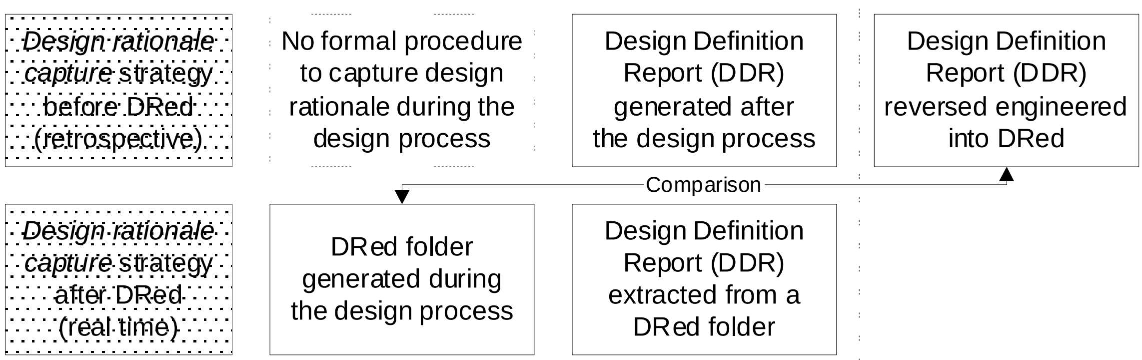

Figure 2. Design rationale capture strategy before and after DRed

The richness of the information recorded using DRed was evaluated by comparing the average number (per document) of *answers per issue* and *arguments per answer* captured in DRed design folders and DDRs. The way these figures were calculated requires some explanations. The *answers per issue* were estimated considering both the accepted and rejected answers. The *arguments per answer* were estimated considering both the pro and con arguments.

Analysis of DRed issues

The analysis of the issues was conducted on a DRed data set including 19 folders, 39 documents and 741 elements captured by seven designers. 16% of the element types were issues, 38% answers and 46% arguments. The design tasks undertaken by the designers at the time in which they documented this data were variant designs, i.e. the work usually involved incremental innovation to extend existing product solutions.

Table 5 presents the distribution of the issue elements in the *nature* category.

Table 5. A: Nature category

TYPE	EXAMPLE	% of total
1 Question	***How could the need for a dust cap be eliminated?***	75%
2 Consideration	*Architectural constraints and variables*	25%

The results showed that a quarter of the issue elements were phrased as a consideration, i.e. the guideline to use a question was not followed. This approach was adopted by only one designer. The data produced by this designer differed from that of the other designers both in its nature and richness. In several cases, this data was found to be very brief and therefore difficult to understand. This finding led to the decision to leave out the data produced by this designer. With this exclusion, the DRed data set included 17 folders, 32 documents and 687 elements captured by six designers.

Table 6 presents the distribution of the questions in the *problem* category.

Table 6 – B: Problem category

TYPE	EXAMPLE	% of total
1 Diagnosis	*Why did the Trent 800 IPT disc rim design temperature exceed the design value?*	10%
2 Design	*How can I maintain the disc temperature below design value?*	85%
3 Process	**How to determine the size of the problem?**	5%

The results showed that the designers captured predominantly questions to address design problems. The questions to address diagnosis and process problems were significantly lower. In general, data analysis showed that the questions to address diagnoses were captured at the beginning of a DRed document and were followed by design questions. This finding indicated that DRed structures were used by designers in a similar way to Design Definition Reports (DDRs) where the problem diagnosis precedes the problem solving.

Table 7 presents the distribution of the questions in the *objective* category.

Table 7 – C: Objective category

TYPE	EXAMPLE	% of total
1 Information	*What material does the Trent 800 use for this part?* (from previous research)	0%
2 Confirmation	*Are suitable materials available?* (from data set)	2%
3 Comparison	*What are the differences in inspection requirements between a class 01 and a class 02 forgings?* (from previous research)	0%
4 Constructive generation	*How can I maintain the disc temperature below design value?* (from data set)	61%
5 Explanatory generation	*How does oil scavenge from that side of the chamber?* (from previous research)	0%
6 Analysis	*How much heat energy can be removed from oil system?* (from data set)	36%
7 Evaluation	*How does this compare to the potential heat build in today's arrangement?* (from data set)	1%

The results indicated clearly that the majority of the questions were classified under two of the high-level objectives, i.e. *constructive generation* and *analysis*. These questions were formed to generate new design solutions and to establish the consequences of using these solutions by carrying out simulation and calculations. Designers did not form questions that were classified under the other two high-level objectives, i.e. *explanatory generation* and *evaluation*. The questions to undertake explanatory generation are generally formed to explain existing solutions. It is therefore not surprising that designers did not capture them using DRed. The questions to undertake evaluation are formed to identify the value of design solutions. A possible explanation for having very few of these questions is that designers carry out evaluation by linking pro and con arguments to design solutions. This means that the evaluation of a design solution is undertaken implicitly.
The results also showed that designers did not capture questions without an objective and with low level objectives, i.e. *information*, *confirmation* and *comparison*. This indicates that designers predominantly used DRed to capture questions to reason about their design issues.

Analysis of DRed syntax

The analysis of the syntax was conducted on a DRed data set including 17 folders, 32 documents and 687 elements. These elements were connected by the six designers using 716 links. As DRed syntax defines nine link types, the mean frequency of use of each link type is approximately 80. Data analysis showed that the distribution of the frequency of use of the nine link types was very dispersed. Based on this finding, it was decided to cluster the nine frequencies in four groups, namely *rarely*, *occasionally*, *frequently* and *very frequently*, see Table 8. *Link type* 9 was specifically referred to when discussing Table 4.

In most cases a DRed document consists of a repeating sequence of *issue-answer-argument*. This sequence is formed by linking an answer to an issue (link type 2) and an argument to an answer (link type 3). It is therefore not surprising that these two link types were used *frequently* and *very frequently* respectively. In order to develop further the *issue-answer-argument* sequence, an issue can be attached to any of the three basic elements. It is interesting that designers *occasionally* attached new issues to answers (link type 4) and *rarely* to arguments (link type 5) and issues (link type 1). Although arguments were very frequently attached to answers, the analysis showed that arguments were *rarely* attached to issues (link type 6) and to other arguments (link type 7). New answers were *rarely* attached to existing arguments (link type 8).

Table 8. Link types and frequency of use

	VALID LINK types	Frequency of use
1	I ß I	Rarely
2	I ß A	Frequently
3	A ß AR	Very frequently
4	A ß I	Occasionally
5	AR ß I	Rarely
6	I ß AR	Rarely
7	AR ß AR	Rarely
8	AR ß A	Rarely
	INVALID LINK type	
9	A ß A	Occasionally
Rarely: below 5%; Occasionally: around 10%; Frequently: around 24%; Very frequently: around 46%.		

The use of this link type implied in most cases the formation of an implicit issue, i.e. an issue that is considered but not recorded. The problem of using links that entail the formation of implicit issues was encountered also when designers attached new answers to previous answers (link type 9). Although this link was considered invalid, designers *occasionally* used it. Two possible reasons were identified for this behaviour. The first is associated with DRed training. The second is associated with a designer's need to streamline the documentation process. Complex engineering processes are often very time consuming to capture so it can be that designers used this link type to speed up the capture of design rationale by omitting the issues.

Comparison of the information recorded in DRed and DDRs

The comparison of the recorded information was conducted on a DRed data set including 4 folders, 17 documents and 302 elements and a DDRs data set including 4 folders, 4 documents and 232 elements. Although the two data sets include the same number of folders, they vary quite significantly in the number of documents. The reason for this difference is mainly due to the way the DDRs were reversed engineered into DRed. The design rationale in each report was always represented through one document only, i.e. the rationale was never distributed across different documents using tunnelling links. The DRed data set used to carry out this part of the research was selected from the 19 folders, 39 documents and 741 elements of the original data set with the aim of identifying the data documented in more detail and with the greater accuracy.

Table 9 presents the average number (per document) of *answers per issue* and *arguments per answer*.

Table 9. Comparison of recorded information

	DRed	DDR
	Average on 4 folders and 17 doc	Average on 4 folders and 4 doc
Answers per issue	2	1.5
Arguments per answer	2	1

Two important results were obtained. The first is that DRed facilitates the capture of nearly two answers per issue compared to one and half of a Design Definition Report. The second is that DRed encourages designers to document nearly double the number of the arguments for designing a certain solution that would be documented through a Design Definition Report.

Further work

This paper has presented an analysis of the design information recorded using DRed. The research developed an understanding of the nature of DRed issues and syntax; and demonstrated that the use of DRed improves the richness of the recorded information. Further work is required to confirm the preliminary results of this research. Plans to collect new and larger data sets have been made. Long-term aims of this project are also to establish if DRed improves the clarity of the recorded information and has a beneficial effect on the design behaviour, by prompting design thinking and helping designers view their design processes. In order to address these aims, a proposal has been made to conduct an experiment with teams of designers working with and without the support of DRed.

Conclusions

The analysis of 19 DRed design folders enabled the development of an initial understanding of how seven engineering designers used DRed. The research found that DRed issues were predominantly phrased as questions. These questions were mainly formed to address design problems. Using DRed, designers captured mostly questions to address the constructive generation and analysis of new solutions. A methodology was developed to evaluate the richness of the information recorded using DRed. The engineering processes captured and structured in DRed, compared to those presented in the DDRs, were found to be richer in the number of recorded design solutions and in the number of pro and con arguments underpinning those solutions.

Acknowledgements

The authors acknowledge the support of EPSRC, Rolls-Royce and BAE SYSTEMS through the UTP for Design, and would particularly like to thank Michael Moss for providing ideas and feedback.

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