INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

ENGINEERING DESIGN BY INTEGRATED DIAGRAMS

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ABSTRACT
The Design Rationale editor (DRed), an IBIS derivative, originally developed to support the capture of design rationale, has progressively evolved into a tool to map a unified information space covering product planning, specification, design, and service. The paper presents research to extend the functionality and the notation of the DRed tool to support the generation of new diagram types. A novel approach to designing and its documentation by integrated diagrams is proposed, formalised into a templated structure and illustrated by means of a case study in the aerospace engineering industry. Up until now the approach has been taught for one year to engineering graduates involved in the training programme of the collaborating company. The results have shown that creating large digital information spaces is feasible, and delivers benefits to its users.

Keywords: diagrams, IBIS, information management, engineering design

1 INTRODUCTION
In current manufacturing organizations, engineering designers receive considerable support through a wide range of design methods, e.g. Computational Fluid Dynamic, Computer Aided Design, etc. However, little aid is offered in representing and integrating the information used and produced during design activities. The majority of design information is captured by designers in personal journals and then summarised in technical reports at the end of projects. Technical reports, the main digital corporate source for design information together with CAD models in PLM systems, capture only fragments of design processes. Enabling real time documentation of design information has the potential to deliver more comprehensive descriptions of design processes. However, the capture of design information through linear text documents is a challenge because of the complex and fast-flowing nature of design activities. Diagrams seem to offer help in the rapid mapping of design information, seeing patterns and achieving insights. Facilitating human cognitive processes, diagrams can be seen as lending structure to designers' thoughts. A diagram can be defined as a simplified visual model of a thing, composed of graphical elements annotated with text fragments (symbols, words, or short phrases) meant to capture key concepts entities and relationships [1]. The content of a diagram can focus on any aspect of interest. Layout and style of diagrams are as important as content. In fact, interpretation of the design information captured in a diagram is linked to the structure and position of its nodes. Research in information representation and increased computing capabilities are offering new flexible diagramming tools. Editing and maintaining diagrams has recently become significantly easier than it used to be. A review of the literature on the use of diagrams has shown that no single diagram can support all types of information managed by designers in the design process [1]. Therefore, several types of representation are necessary to help designers use and create new design information. Previous research on diagramming tools has aimed at modelling different aspects of design projects through a range of representational techniques [2]. However, it was found that either the tools have supported techniques not mature yet for industrial use or the application of the tools has been dependent on the presence of able facilitators.
This paper presents research in collaboration with the aerospace department of a major power system company to understand how designers can be supported in using and representing design information in engineering design projects. We put forward the idea of using a set of diagrams to represent functional, behavioural and structural thinking in design. Based on the analysis of group design activities undertaken by graduate engineers involved in real design tasks, a novel approach to designing by integrated diagrams was developed, communicated through a templated structure and tested. The structure is supported by the Design Rationale editor (DRed) tool, an IBIS-derivative [3],

initially developed to capture and model design rationale. Its functionality and notation, originally including only the well-known IBIS elements, have progressively been extended and specialized to use the tool in the service of new methods for information representation. The tool has, therefore, evolved to become a platform for editing and maintaining a range of different diagrams. The paper presents the key diagram types that can currently be generated using the tool, and a case study of its application in design projects undertaken by graduate engineers.

2 BACKGROUND ON THE USE OF DIAGRAMS

Previous research has proposed several diagram types to support design activities. Mind maps have been used for centuries to help in thinking and learning [4]. Mind mapping involves writing down a central idea and thinking up new and related ideas, which radiates out from the centre. In engineering, mind maps have been used for a wide range of purposes including creating 'to do' lists, note-taking individually and in meetings, formulating specifications, brainstorming, trouble shooting, etc. Fault Tree Analysis (FTA) developed in the sixties is an example of early industrial use of diagrams in the design process [5]. FTA is aimed at supporting the analysis of product failures by mapping causal chains with a top-down approach based on a graphic model. Another technique for failure analysis developed in those years is the Ishikawa diagram, also known as fishbone diagram [6]. In this technique, the problem of interest is entered at the right of the diagram as the 'head' of the main backbone, and the possible causes of the problem are drawn as bones of the main backbone. Again in the sixties Paynter introduced the idea of Bond Graphs [7], a form of diagram representing the behaviour or function of power-transforming engineering systems in a concise, energy domain neutral and computable way.

Across the seventies and eighties, various new types of diagram were proposed. The Issue Based Information System (IBIS) was introduced by Kunz and Rittel with the aim of supporting coordination and planning processes [8]. IBIS consists of a tree or directed graph, where nodes representing issues to be resolved, alternative solutions, and arguments in favour and against, are linked by arcs. Concept maps were developed by Novak in the course of a research program at Cornell where he sought to follow and understand changes in children's knowledge of science [9]. Concept maps are graphical tools for organising and representing knowledge. They include concepts, usually enclosed in boxes of some type, and connecting arrows between pairs of concepts where a relationship of some type can be specified. The Function-Means tree was proposed by Andreasen [10] to model the Function-Means law originally published by Hubka in 1967 [11]. Finally, the Function Structure was introduced by Pahl and Beitz [12] to model the functions required in a new product.

Among these concepts, IBIS has attracted significant interest because of its simplicity. The research to develop computer support for this diagram and understand its applicability is still ongoing. In 1987, Conklin proposed gIBIS, a computer based system to develop diagrams for exploratory policy discussions [13]. There years later two variants of the IBIS concept known as Question Option Criteria (QOC) and Procedural Hierarchy of Issues (PHI) were proposed by MacLean [14] and McCall [15] respectively. In 1997 research in the architecture domain led to the proposal of another formalism known as Issue Concept Form (ICF), with a high degree of similarity to IBIS [16]. In the meantime, the interest in computer support for IBIS-like diagrams led to the evolution of gIBIS into QuestMap [2], a software tool which combines hypertext functionality and a structured modelling framework known as Conversational Modelling. Further research and development led to its subsequent evolution in Compendium [17]. The Compendium dialogue mapping tool has attracted a large research community which is focusing on the use of the tool for collective sense-making. Several successful case studies in industry were undertaken by the researchers behind QuestMap and Compendium and an example can be found in [18]. However, it seems that the use of these tools has always been dependent on the presence of a facilitator and has never seen regular and long lasting use in industry. In 2003, a new IBIS derivative termed the Design Rationale editor (DRed) was developed at the Cambridge Engineering Design Centre in collaboration with a large aerospace company [19]. Over the last years the tool has been developed as reported in [3, 20, 21] and has experienced an increasing use both individually and collaboratively.

Concept maps have received, similarly to IBIS, considerable attention and their use has been both in education to support learning and in business for tasks like note-taking and new knowledge creation. An example of their application to model the information used and produced in engineering design activities can be found in [22].

Although Function Means trees and Function Structures received less interest than IBIS and Concept maps, both concepts were used as a basis for further research. For example, Bracewell and Sharpe combined Function Means trees with a bond graph based representation of function to support computational synthesis of mechatronic devices [23, 24]. Hansen and Andreasen instead proposed to use the Function Means tree to synthesise mechanical artefacts rather than just to explain designs [25]. In particular, they presented two formal approaches, namely a 'design process oriented approach' for design situations where the required functionality is new and an 'artefact oriented approach' for design situations based on past designs. Stone, starting from a Function Structure diagram in Pahl and Beitz-style, proposed a way to extend such diagram to generate a product architecture and its composing modular concepts [26].

Other diagram types recently proposed to support engineering design activities are the Product Ideas Tree (PIT) developed by Jones [27], which claims to be useful for eco-innovation, and the Product Design Schematic (PDS) and the Product Architecture Schematic (PAS) described by Salustri [1].

Overall the literature review showed that numerous attempts have been made to enable computer based generation of diagrams to support design activities and that some of these tools have been extended to support specific modelling frameworks. However, it seems that either these tools have supported techniques not yet sufficiently developed for industrial use, e.g. advanced computational synthesis, or the use of the tools has been dependent upon the participation of able facilitators. Therefore, the need to develop an approach to designing through diagrams that is ready for industrial use, and can be easily applied by independent users was identified.

3 METHODOLOGICAL APPROACH

The practical approach taken aligns with the design research methodology developed by Blessing et al. [28] and its extension to research and develop software tools for designers [29]. Both methodologies consist of four stages: Criteria, Descriptive Study I, Prescriptive Study, and Descriptive Study II. In the first stage, success criteria already identified in the information management literature were borrowed to map the benefits of designing by integrated diagrams. In the second stage, the design activities undertaken by two waves of trainees involved in the Design & Make project at the collaborating company were analysed to identify opportunities for improvement. In the third stage, insights gained during Descriptive Study I were used to propose a novel approach to designing by integrated diagrams and then to develop a templated structure. In the fourth stage, new waves of trainees were introduced to the novel approach by training and asked to use it in their Design & Make project. The research reported in this paper focuses mainly on the third and fourth stage of the research methodology.

4 THE DRED TOOL

The initial research and implementation of the DRed tool are presented and discussed in [19]. In this section, we introduce the initial DRed concept and its evolution from tool to support one type of information representation to multiple types.

4.1 The original DRed concept

DRed was a simple software tool for design rationale capture, descended from the venerable gIBIS [13], which was intended as a more functional replacement to the traditional bound designer's journal. The rationale was captured in a set of charts, each displaying a graph of nodes linked by directed arcs, and stored in a single file kept in a design folder. Charts appeared as zoomable, scrollable, 2-dimensional surfaces of unlimited extent scrolling rightwards and downwards. It was however, considered good practice to limit the contents of a single chart to that which could be printed at a readable scale. There was no inherent hierarchical decomposition of charts – every chart in the design folder existed at the same level. DRed elements (nodes) were normally created, positioned, and linked manually by the user. The user chose elements, from a predefined set of element types, namely Issue, Answer, Pro, Con, Text, Task and File, see Figure 1. The original set was not claimed to be comprehensive for every possible application, but experience showed that they seemed to be a suitable "core set." If additional types were found to be necessary, simple text elements named with a suitable heading could be used in the interim. The graphics aimed to clearly distinguish each type from the others. Any element on a chart could be linked without restriction to any other, and any element can easily be converted from its existing type to another.

Each element type had a predefined set of statuses, signified by changes in colour and geometry of the background shape or font style of the text, see Figure 1. These statuses were changed by the designer as work progresses, generally from "unresolved" to "resolved," although earlier decisions might also be revoked when new information was uncovered or problems realized. This gave a clear view of the progress of the design and allowed the knock-on effects of revoked decisions, or the discovery of new information, to be propagated through the rationale. While colour was used to make the rationale clearer to interpret on screen, the differently shaped graphics were designed to make the meaning unambiguous in greyscale hardcopies.

Unlike most other gIBIS-derived tools, DRed only had a single type of link, a unidirectional arrow, which represented some sort of dependency, see Figure 1. The meaning of that dependency was inferred from the types of the elements at each end of the arrow. This was because feedback from users indicated that they found the meaning of links clear from the types and contents of the nodes, so forcing them to specify the link semantic explicitly seemed to be unnecessary. As a rule of thumb, when the designer changed the status of any element, arrows should generally point from it to all other elements, the statuses of which should be reviewed as a direct consequence of that change.

Dependencies between elements belonging to different charts were made via tunnelling links, which allowed bi-directional hyperlinking. These appeared to tunnel into the work-plane, reappearing elsewhere and continuing on to their destination element, see Figure 1. Tunnels might also be used on a single chart to avoid links crossing confusingly, or where the two linked elements were so widely spaced that they could not both be viewed without scrolling. Each of the pair of tunnel mouths was shown as small circular icons. Double clicking a tunnel mouth, or hitting the return key while a tunnel mouth was selected, moved the mouse pointer "through the tunnel" to the opposite mouth, displaying its chart and leaving the mouth visible and selected. Thus having glanced at the surroundings of the far end of the tunnel, the user could immediately return if desired by double clicking or hitting the return key once again. Such links permitted the rationale for larger design projects to be distributed across multiple charts, and laid out legibly, while facilitating navigation between them.

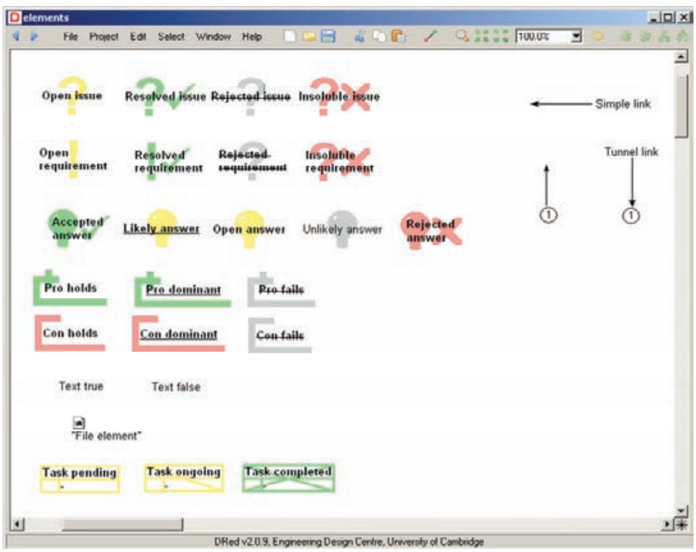

Figure 1. DRed elements and statuses, and links

Files from any other application used as part of the design process might be linked into the rationale using elements of the File type. If these files were created as part of the design project, they were stored in the design folder and referenced by a relative file path. Alternatively, the document might be on a remote server. The default was for the file element to be displayed as a small icon representing the type of the referenced document. However, as an alternative, a screen captured bitmap of the document contents could be displayed on the DRed chart. DRed links anchored to an element normally terminated on the element border, positioned to point at the centre of the element. However, for these bitmap graphical elements, links could be anchored to a specific location in the graphic. This enabled for example, references to CAD files to be displayed within DRed as a view of the screen captured from the tool, with links anchored to the location of individual features, labelling or expressing issues related to them. By double clicking the file element, the referenced document was loaded into its software application and displayed.

The File element could also be used to capture freehand design sketches, whether optically scanned from paper, or if DRed was used on a Tablet PC, directly drawn on the computer screen using the pressure sensitive stylus. The use of File elements to associate files with related nodes in the rationale, allowed DRed to provide a unified navigable map of the emerging design folder. Once finally completed and approved, the folder could be made available for searching and read-only browsing, by simply copying it into the file space of a standard intranet or internet web server. The repository was then accessed by using a standard web browser, configured with DRed as a helper application.

4.2 The first evolution of the DRed tool

The DRed tool, after its initial introduction in Rolls-Royce, has seen a steady increase in use and generally favourable comments leading to its acceptance as part of the standard Product Lifecycle Management (PLM) toolset, and deployment across the company worldwide [3]. Close collaboration with the collaborating company has enabled the DRed development team to gather important user feedback and to implement it in order to improve the tool. In addition, the availability in the company of a graphical tool like DRed has progressively stimulated its engineers and researchers to think how to support product development activities through other diagram types. The service engineering community has been the recipient of the first application of the tool outside the design rationale domain. A method, alternative to the fishbone diagram, to identify and map the root causes behind product failures was required. Working with service engineers, a diagram to map in a logical way cause-effect chains with IBIS-like justifications was developed and tested [3].

4.3 The second evolution of the DRed tool

Following the promising results in the use of the root cause analysis diagram, DRed's bi-directional hyperlinking functionality was extended to and from bookmarked locations in MS Office documents [21]. This new functionality was introduced under the assumption that if users could create bidirectional hyperlinks between DRed elements and selected locations in a range of external document types, then this might support the capture of a unified information space covering the product planning, specification, design and service.

In the subsequent years, two new applications of the DRed tool emerged. The first was aimed at supporting designers in the mapping of useful and harmful relationships between the elements of a system, a concept published as part of a 1997 software patent application by the TRIZ vendors Invention Machine Corporation [30]. At the collaborating company, this technique, known as Functional Analysis Diagram (FAD), was already effectively used for some years, generally in the context of TRIZ workshops convened to address a particular problem. Designers used to create FADs in Microsoft PowerPoint with the aid of a simple template. The normal practice is to define the elements of a system, users and other resources using nouns, and the behavioural relationships using verbs. In order to support the use of FADs, two new elements were introduced into DRed, namely Block and Relationship, see Figure 2.

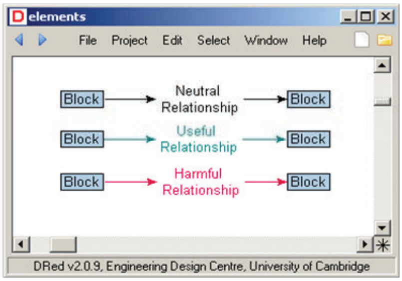

Figure 2. New DRed elements and statuses

The second application focused on mapping design requirements and evaluation criteria in order to support the graduates involved in the training programme within the collaborating company. A method to map functional and non-functional requirements as well as evaluation criteria using the basic elements in the initial DRed tool was therefore developed.

The new diagram types supported by the DRed tool and the promising results from their use set the basis for this research. Starting from the five diagrams discussed above, i.e. design rationale, root cause analysis, functional analysis diagram, requirement map and criteria map, the authors of this publication developed an approach to designing and its documentation through integrated DRed diagrams. The work reported on this subject is the result of a two-year collaboration with the managers of the graduate training programme at the collaborating company and the trainees involved in the research.

5 TEMPLATED STRUCTURE FOR DESIGNING BY INTEGRATED DIAGRAMS

Analysing the design activities carried out by engineering graduates involved in the Design & Make project at the collaborating company, opportunities to map design information through new DRed diagrams were identified. Therefore, the initial set of DRed diagrams including five types was extended. For the purpose of communicating to the graduates how and when to use the different diagram types, a templated structure was developed in DRed. The structure is composed of a top level chart, which performs the function of hub for the diagrams, and a set of dependent charts each of which contains a different diagram. The development of the structure and its diagrams was informed by previous research and an iterative research process consisting of observing group design activities, proposing methods to map design information and testing their application.

5.1 Top level chart

The top level chart consists of a three-level hierarchy of issues and a level of answers. The issues are used to break down a project into its main process steps, see Figure 3 and 4. The root of the issue hierarchy is the project statement, which is decomposed into: (1.1) project management; (1.2) problem formulation, structuring and understanding; and (1.3) solution generation, evaluation and realisation. A subsequent level of issues is used to obtain a finer set of process steps, see Figure 3 and 4.

The answers are attached to the issues at the lowest level. These are to be interpreted as methods to represent and process design information in order to accomplish a specific process step, e.g. the Functional Analysis Diagram is a method to analyse an existing system, see red dashed rectangle in Figure 3. The top level chart also shows that the answers are tunnel linked to other DRed charts where the individual diagrams are represented. All the elements in the chart are in the open status (yellow) to mean that the chart has not been started yet.

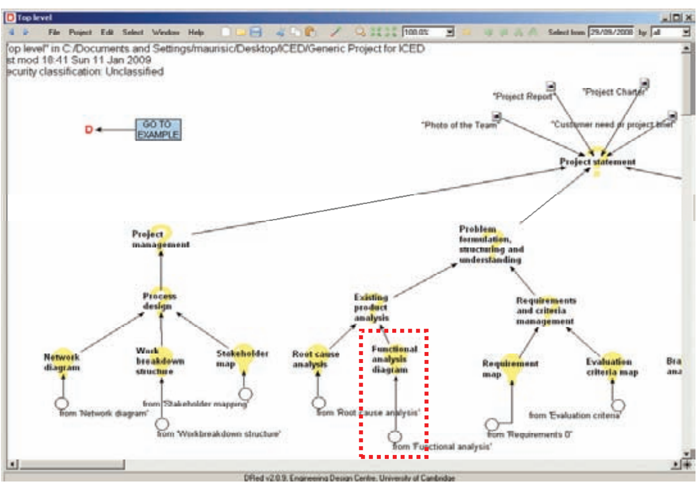

Figure 3. Top level chart (part 1)

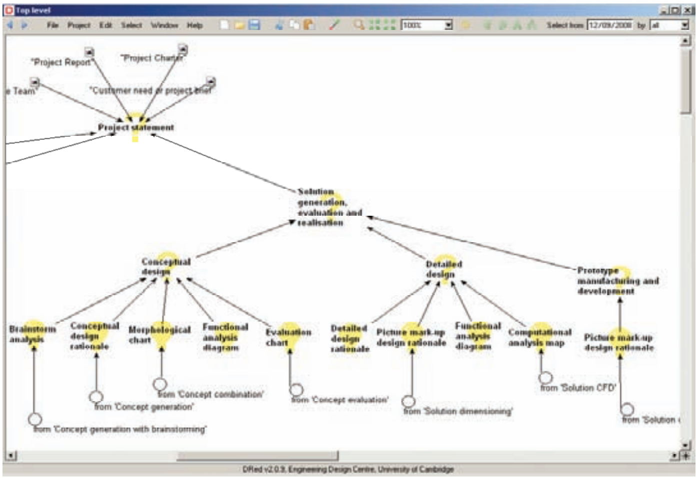

Figure 4. Top level chart (part 2)

Sections 5.2, 5.3 and 5.4 present the diagrams types under each of the three main process steps.

5.2 Diagrams for project management

The templated structure includes three diagram types for project management. The Activity Network Diagram (AND), also known as Project Evaluation and Review Technique (PERT) chart, is a method to analyse the tasks necessary to complete a project. This diagram is built using only the DRed task element, see Figure 1 for a picture of the element. The structure of such diagram grows from left to right following the chronological development of the project. The Work Breakdown Structure (WBS) is a method to define and organise the total scope of a project. Each element of a WBS has to provide a brief description of the task to be performed. A WBS is generally organised around the key physical elements of the project instead of the work needed to achieve them. This diagram, similarly to the AND, is built using task elements by arranging them in a tree like form. The Stakeholder Map (SM) is a method to identify the people who will be affected by the activities of a project and its outcomes, prioritise their engagement and map their profiles. A SM is created using the conventional DRed elements, i.e. issue, answer, pro and con nodes, and generally has a tree like form.

5.3 Diagrams for problem formulation, structuring and understanding

Four diagram types are proposed to explore and analyse design problems. The Root Cause Analysis (RCA) diagram is a top-down method to identify the failure/s within an existing product. The diagram is generally constructed starting from a critical event and performing a backward search to identify the chain of causes and effects. A key attribute of the method is the identification and capture of the evidence in favour and against each of the elements in the causal chain. A RCA diagram is created using the conventional DRed elements, i.e. issue, answer, pro and con nodes, and placing them in a tree like form. The Functional Analysis Diagram (FAD) is a method to analyse useful and harmful relations between the components and resources of a system. A FAD is built using the block and relation nodes and it is a form of concept map. The Requirement Map (RM) is a method to list the requirements of the project and divide them into functional, i.e. functions, and non-functional, i.e. goals or qualities of the system to be designed. The Evaluation Criteria Map (ECM) is a method to list the criteria to be considered during the evaluation of a solution. An ECM is created using the conventional DRed elements and placing them in a tree like form.

5.4 Diagrams for solution generation, evaluation and realization

Eight diagrams are proposed within this section to reason with design concepts and the chosen solution. The Brainstorm Analysis (BA) diagram is a method to map and analyse the concepts developed during a conventional brainstorm. The starting point of this diagram is a DRed issue and a photographic image of the concepts sketched on a flipchart or a whiteboard by a design team. The image is subsequently annotated with DRed answers and arguments, where the answers have links anchored to x and y locations of concepts in the image. A BA diagram is therefore built using a mix of graphical images and conventional DRed elements. The Conceptual Design Rationale (CDR) diagram is the conventional IBIS method of proposing answers to design issues and capturing the rationale for each answer as a set of arguments. The Morphological Chart (MC) is a method to provide a structured approach to concept generation by combination of alternative partial solutions. This method can help a designer or a design team to generate a wide range of alternative solutions to a design problem through a detailed analysis of form and configuration. In DRed, a MC can be represented in the form of either a matrix using by-directional links to MS Excel or a diagram. The Functional Analysis Diagram (FAD), already introduced for the purpose of analysing existing systems, is often used in this context to analyse the relationships between the components of an emerging system. The Detailed Design Rationale (DDR) diagram uses the same structure proposed for the CDR diagram. The Computational Analysis Map (CAM) is a means of linking the pictorial results of computational analyses like CFD or FEA to the concepts under consideration and therefore to form arguments that are justified by evidence. Finally, the Picture Mark-up Design Rationale (PMDR) diagram is a method to identify the issues to be addressed and their answers from a picture based representation of the system being designed.

6 CASE STUDY: THE VENT RESTRICTOR REDESIGN

As yet, the templated structure for designing by integrated diagrams has been used by two waves of trainees involved in the graduate training programme at the collaborating company. The trainees have applied the structure in the Design & Make project, one of the activities of the training programme. The project runs every three months and generally involves 14 graduates working in teams of 3 or 4 members. This makes the project an ideal opportunity to propose and test new research ideas. One of the teams who used the templated structure was tasked with redesigning a restrictor located on a vent line departing from one of the bearing chambers of a gas turbine. The team produced approximately 20 DRed charts at the completion of the project which were sometimes created and edited in a collaborative way, other times individually and in general contained design work from all the team members. Three of these charts are now presented. Figure 5 illustrates the top level chart for the Vent Restrictor project. It is noticeable that most of the nodes are now in the accepted status (green) to mean that the team went through the process steps specified in the issues nodes and produced the diagrams described in the answer nodes. However, it can also be seen that two answer nodes are still in the open status (yellow) to mean that those diagrams were not started yet.

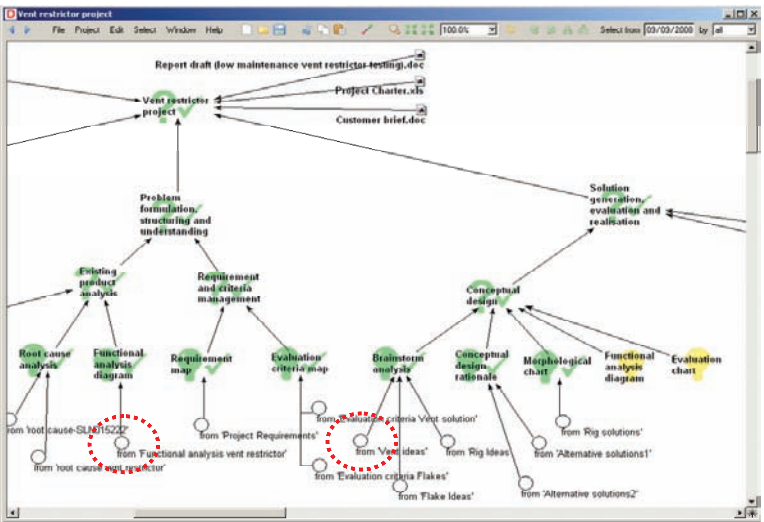

Figure 5. Top level chart for Vent Restrictor Project

The answer nodes in the top level charts have one or more tunnel links leading to other DRed charts where the specific diagrams are developed. The charts marked with a red circle in Figure 5 are now presented, i.e. the Functional Analysis Diagram and the Brainstorm Analysis.
The Functional Analysis Diagram was used to analyse the exiting vent restrictor design and to identify opportunities for improvement, see Figure 6. An image of the bearing chamber helped the team focus on the main components and resources of the system and create the initial block elements. At this stage, the relationship elements were progressively specified with green and red colours used to distinguish useful from harmful actions. The understanding extracted from the use of this chart was translated into a requirement reported into the Requirement Map, and subsequently used to generate a design question for the concept generation phase.

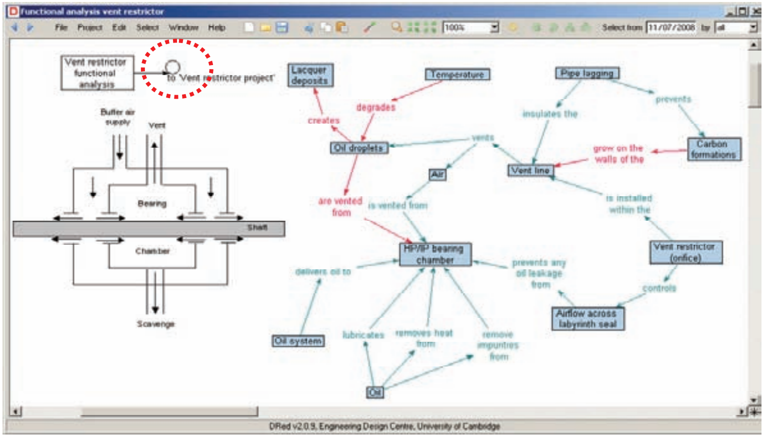

Figure 6. Functional analysis diagram for vent restrictor

The Brainstorm Analysis chart was used in the early conceptual design phase to reflect on the concepts proposed during a conventional brainstorming by capturing pro and con arguments, see Figure 7. Each answer has a set of arguments and points to its sketch therefore facilitating the reconstruction and interpretation of the design process.

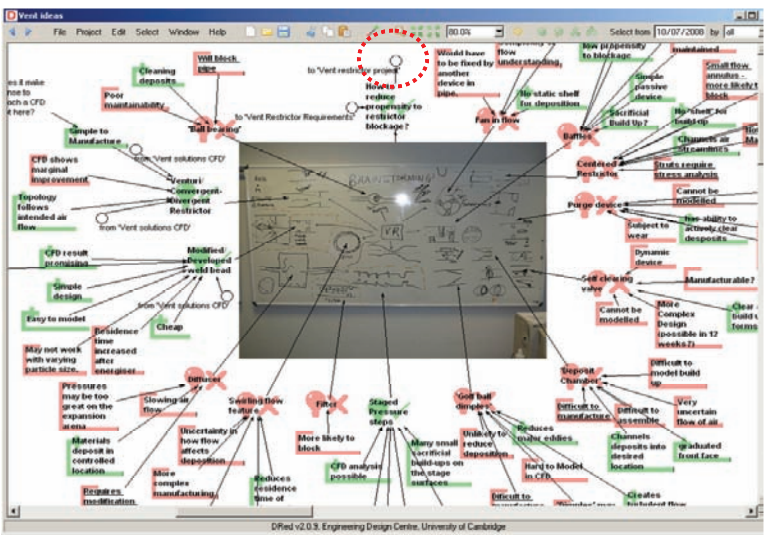

Figure 7. Brainstorm analysis chart

The design team found the analysis mapped into this chart very useful to select the three concepts to take to the next design phase. These can be identified in the accepted solutions marked in green. It is noteworthy that this chart and its layout were spontaneously proposed by the trainees involved in this project, and subsequently proposed and encouraged as a standard practice by the authors.

7 EVALUATION

Approximately 60 engineering graduates have been trained in designing by integrated DRed diagrams in 2008. Only the graduates who took the Design & Make project in the second half of the year were trained using the templated structure and examples. In the first half of the year the training was delivered just by examples. The graduates were trained during a one day course delivered by the authors at the collaborating aerospace company. The training was designed to include four main parts:

- An overview of the design process that forms the basis of the DRed top level chart;
- An introduction to the mechanics of the DRed tool;
- A presentation and explanation by examples of the diagrams under the headings *project management*, and *problem formulation, structuring and understanding*;
- A presentation and explanation by examples of the diagrams under the heading *solution generation, evaluation and realisation*.

After parts two, three and four, practical exercises were used to deliver initial experience of the mechanics of the tool and the generation of DRed diagrams. The training is generally delivered at the end of the first week of the Design & Make project to enable the trainees to develop diagrams based on their engineering challenges.

So far this novel approach to designing by diagrams has been received with interest and enthusiasm. In many occasions the participants have reported that drawing diagrams has enabled them to gain a deeper understanding of their problems. After the Design & Make project, one of the waves of graduates trained through the templated structure (12 participants) was supplied with a questionnaire to evaluate the newly proposed approach. The questionnaire was designed to include four levels of evaluation, i.e. reaction, learning, behaviour and results, as proposed by the Kirkpatrick model for evaluating tools and methods in industry [31]. The results of the evaluation are presented here:

- Reaction: The graduates were asked how satisfied they were with the novel approach to designing and how relevant the approach was to the D&M project. Satisfaction and relevance of the approach were measured in four tasks: writing, reading-interpreting, editing and presenting-explaining DRed charts. The scale employed was: very satisfied/very relevant; satisfied/relevant; not sure; unsatisfied/irrelevant; very unsatisfied/very irrelevant. On average eleven out of twelve participants replied to be either satisfied or very satisfied and considered the approach either very relevant or relevant to the D&M project.
- Learning: The graduates were asked how easy it was to learn the novel approach. Ease of learning was again measured in the context of the four tasks introduced above. The scale employed was: very easy; easy; not sure; difficult; and very difficult. All the participants answered that it was either very easy or easy to learn the approach.
- Behaviour: The graduates were asked how the use of the novel approach affected their design thinking and their view of the design process. The scale employed for both questions was: improvement; slight improvement; no effect; slight hindrance; and hindrance. Eleven graduates out of twelve answered that the approach either gave an improvement or a slight improvement to both their design thinking and their view of the design process.
- Results: The graduates were asked how the novel approach affected: - the prompt of aspects that one would not have thought otherwise; - the number of alternative solutions generated; and - the evaluation and decision between solutions. The scale adopted was as for the questions in the behaviour section. On average 10 out of twelve participants reported that DRed charts delivered either an improvement or a slight improvement in prompting design considerations, in the number of alternative solutions produced and in the solution evaluation process.

8 CONCLUSION AND FURTHER WORK

A key challenge in engineering design research is that of enabling designers to capture in a digital way design information of the type that is generally documented in personal design journals. This would enable manufacturing organizations to create large corporate repositories of past projects information. The Design Rationale editor is an IBIS derivative developed in collaboration with a large power aerospace company to document design rationale. The tool, since the early stages of its introduction into the collaborating company, has received favorable comments and has shown how a neat implementation of an IBIS derivative can allow designers to create clear design information diagrams. This paper has reported on extensions to the functionality and notation of the DRed tool in order to enable the capture of a unified information space covering product planning, specification, design and service. Based on previous DRed research and the analysis of Design & Make projects, a novel approach to designing by integrated diagrams is proposed, formalized into a templated structure and illustrated by means of a case study. The diagrams included in the structure have evolved based on the lessons learnt from their application within the Design & Make project. Overall, the results have shown that capturing a large digital information space composed of integrated diagrams is feasible, and users find it beneficial to draw these representations.

ACKNOWLEDGEMENT

The authors acknowledge the support for this research from the Rolls-Royce University Technology Partnership (UTP) for Design. The research reported in this paper was also supported by the UK Engineering and Physical Sciences Research Council (EPSRC) under grant number EP/C534220/1, through the “Immortal Information and Through-Life Knowledge Management: Strategies and Tools for the Emerging Product-Service Paradigm” (KIM) project. Finally, the authors would like to thank Jim Wickerson and Roger Fountain, managers of the Rolls-Royce Graduate Design & Make project, for their contribution and constant support.

REFERENCES

[1] Salustri, F.A., Bracewell, R.H., Eng, N. and Weerasinghe, J.S. Visualising early engineering design information with diagrams, *Journal of Design Research*, 2007, ISSN 1748-3050.
[2] Selvin, A., Supporting Collaborative Analysis and Design with Hypertext Functionality, *Journal of Digital Information*, 4, 1999.
[3] Bracewell, R.H, Wallace, K.M., Moss, M., Knott, D.S. Capturing design rationale, *Computer-Aided Design*, in press, DOI: 10.1016/j.cad.2008.10.005.
[4] Buzan, T., Buzan, B. *The Mind Map Book: How to Use Radiant Thinking to Maximise Your Brain's Untapped Potential*. Dutton: Penguin, 1993.
[5] Watson, H.A. *Launch Control Safety Study*, Section VII, Vol. 1, 1961, Bell Labs, Murray Hill, NJ.
[6] Ishikawa, K., *Introduction to Quality Control*, 1990, 3A Corporation, Chapman & Hall, UK.
[7] Paynter, H.M., *Analysis and Design of Engineering Systems*, 1961, The MIT Press, Cambridge, Massachusetts.
[8] Kunz, W., Rittel, H. Issues as Elements of Information Systems, 1970, Technical Report Working Paper No. 131, Institute of Urban and Regional Development, University of California, Berkeley, Berkeley, CA.
[9] Novak, J. D. and Cañas A.J. The Theory Underlying Concept Maps and How to Construct Them”. Technical Report IHMC CmapTools 2006-01, Florida Institute for Human and Machine Cognition, 2006.
[10] Andreasen, M.M. *Machine Design Methods Based on a Systematic Approach – Contribution to a Design Theory*, 1980, Ph.D. Dissertation (In Danish), Department of Machine Design, Lund Institute of Technology, Sweden.
[11] Hubka, V., Der grundlegende Algorithmus für die Lösung von Konstruktionsauf-gaben, 1967, XII Int. Wiss. Kolloquium der TH Ilmenau ‘Konstruktion’.
[12] Pahl, G. and Beitz, W. *Engineering Design*, 1984, London, Springer/Design Council.
[13] Conklin, J. and Begeman, M.L. gIBIS: A Hypertext Tool for Team Design Deliberation. In: Weiss, Stephen and Schwartz, Mayer (eds.) *Proceedings of ACM Hypertext 87 Conference* November 13-15, 1987, Chapel Hill, North Carolina. pp. 247-251.
[14] MacLean, A., Young, R., Bellotti, V. and Moran, T. Questions, options and criteria: Elements of the design space analysis. *Human-Computer Interaction*, 1991, 6, (3&4), pp 201-250.
[15] McCall, R. PHI: A Conceptual Foundation for Design Hypermedia. *Design Studies*, 1991, 12: 30-

41.
[16] Oxman, R.E., Sarid, A., Bar-Eli, S. and Rotenshtreich, R. A Conceptual Network for Web Representation of Design Knowledge. In *International Conference, CAAD Futures' 97*, 1997, Munich, Germany.
[17] Conklin, E.J. *Making sense of fragmentary information: Compendium and the Intelligence Community*, CogNexus Institute, 2002.
[18] Selvin, A.M. and Buckingham Shum, S.J. Rapid Knowledge Construction: A Case Study in Corporate Contingency Planning Using Collaborative Hypermedia. In *Proc. KMaC 2000: Knowledge Management Beyond the Hype*, 2000, Birmingham, UK, Operations Research Society, pp. 48-58.
[19] Bracewell, R.H. and Wallace, K.M. A tool for capturing design rationale. In 14th *International Conference on Engineering Design (ICED'03)*, 2003, Stockholm, Sweden, 185-186.
[20] Bracewell, R.H., Ahmed, S. and Wallace, K.M. DRed and design folders: a way of capturing, storing and passing on - knowledge generated during design projects. In 2004 *ASME International Design Engineering Technical Conferences (DETC'04)*, 2004, Salt Lake City, Utah, USA.
[21] Bracewell, R.H., Gourtovaia, M., Wallace, K.M. and Clarkson, P.J. Extending Design Rationale to Capture an Integrated Design Information Space. In *International Conference on Engineering Design, ICED'07*, 2007, Paris, France August.
[22] Eng, N. *Design of a Cradle to Cradle Biophotovoltaic System*, 2005, Master thesis, Ryerson University Faculty of Engineering and Applied Science.
[23] Bracewell, R.H. and Sharpe, J.E.E., Functional descriptions used in computer support for qualitative scheme generation – 'Schemebuilder', *AIEDAM Journal*, 1996, Special Issue, Representing Functionality in Design, Vol. 10, N. 4, pp.333-346.
[24] Bracewell, R.H. Synthesis based on function-means trees: schemebuilder. In *Engineering Computational Design: Understanding, Approaches and Tools*, 2002, Springer 199-212.
[25] Hansen, C.T., and Andreasen, M.M. Two approaches to synthesis based on domain theory. In *Engineering Design Synthesis*, 2002, (Chakrabarti, A., Ed.), pp. 93-108. New York: Springer-Verlag.
[26] Stone, R. B., Wood, K. L., and Crawford. R. H. A heuristic method for identifying modules for product architectures. *Design Studies*, 2000, 21, 5-31.
[27] Jones, E., Stanton, N.A. and Harrison, D. Applying structured methods to Eco-innovation. An evaluation of Product Ideas Tree diagram, *Design Studies*, 2001, vol. 22, no. 6, pp. 519-542.
[28] Blessing, L.T.M., Chakrabarti, A. DRM: A Design Research Methodology. In: *Proceedings of International Conference on The Science of Design* - The Scientific Challenge for the 21st Century, 2002.
[29] Bracewell, R.H., Shea, K., Langdon, P.M., Blessing, L.T.M., Clarkson, P.J. A Methodology For Computational Design Tool Research. In: *Proceedings of ICED01*, 2001 Paper 122.
[30] Devoino, I.G., Koshevoy, O.E., Litvin, S.S. and Tsourikov, V. Computer Based System For Imaging And Analyzing A Process System And Indicating Values Of Specific Design Changes, 1999, United States Patent 6202043.
[31] Kirkpatrick, D.L., *Techniques for evaluating training programs*, 1959, ASTD, 13 11, 3-9.

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