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IMPROVING DESIGN RATIONALE CAPTURE DURING EMBODIMENT DESIGN

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ABSTRACT

The design of an unmanned air vehicle (UAV) as a part of the DECODE project is used as a case study to measure design rationale capture during the design process. It is observed that the capture of design rationale tends to decrease during the embodiment design phase. The inability to connect rationale to geometry is identified as a probable cause. A solution is proposed to increase the ease of design rationale capture during detail design by creating links between design rationale nodes and the corresponding parameters in the CAD design. Further implementation and testing of these concepts is discussed.

Keywords: Design Rationale, CAD geometry, Embodiment Design, Design Tools, Design Rationale Capture

1 INTRODUCTION

During an engineering design process there are many demands on the designer's time: designing a high quality geometry which is light and cheap enough to be competitive, answering questions from junior colleagues while searching for other information and replying to emails. Any suggestions to devote time to an additional activity will probably not be welcomed.

According to Lee [1] "Design rationales include not only the reasons behind a design decision but also the justification for it, the other alternatives considered, the tradeoffs evaluated, and the argumentation that led to the decision" Capturing design rationale is a time consuming activity, and as is stated by Buckingham Shum et al [2]: "*No designer can be expected to altruistically enter quality design rationale* ***solely*** *for the* ***possible benefit*** *of a* ***possibly unknown person*** *at an* ***unknown point in the future*** *for an* ***unknown task****. There must* ***be immediate value.***" However, capturing the design rationale can aid decision processes [1] and "*... the principal role of an engineer, in the design of an artifact, is to make decisions*"[3].

Marples [4] describes a model for the design process showing the progression of the design including accepted and rejected alternatives, however this system was suggested as a model of the design process rather than a tool for problem solution. Performing the rationale capture as an integral part of the decision process originated as IBIS (Issue-based Information Systems) [5] which was intended to support political and social decision processes. IBIS works by starting with a central problem phrased like a question, the *issue*, possible answers to this question and arguments for, or against, the possible answers. The graphical power of computers enabled the development of graphical rationale mapping systems such as gIBIS [6] or QOC (Questions, Options, Criteria) [7],[8]. These concepts have evolved into today's rationale mapping programs such as Compendium [2] and DRed (Design Rationale EDitor) [9]. A focus of today's rationale mapping programs, especially DRed, is no longer political processes, but engineering design, and it is now used by engineers and engineering companies such as Rolls-Royce [10],[11]. The work at Rolls-Royce remains one of the few published case studies of design rationale capture in a large multinational engineering firm. In an engineering design context there are three main benefits to be drawn from design rationale [12]:

- Creating a coherent view of the information available.
- Improving the design thinking and decision processes.
- Improving documentation to facilitate design reuse and design reviews.

How do we obtain design rationale?

It is important to distinguish between capturing and creating rationale. Design rationale is *created* consciously or unconsciously by the designer during the design process. If there is no rationale the designer has made an irrational decision. Generally designers create rationale for their decisions; however the rationale of the decision process is often not *captured.* The capture of design rationale can be performed by the designer, another entity such as a computer program, or by a combination of the two. Lee, for example, identifies five methods [1]: Reconstruction, record and replay, methodical by-product, apprentice, automatic generation. Design rationale captured by computers without user input is generally more focussed on design reuse and seeks to minimize intrusion on the designer as a result of the rationale capture process. A large number of attempts have been made to obtain a record of the design rationale without human input. For example: attempts have been made to extract rationale from the CAD design process[13],[14], or recover it from associated documents, such as emails [15], however these approaches do not aid the designers with their design task, but may aid future designers who are reusing the designs. During the first DECODE[1] (Design Environement for COmplex DEsigns) case study the rationale was captured as a methodical by-product of the design; this method is the only one which can deliver all the benefits of capturing design rationale, most importantly helping the designers in their decision making tasks.

1.1 design context of the case study

The design activity during which our data was gathered was the design process of a light (sub 20 kg) unmanned air vehicle (UAV), primarily designed for a maritime search task, as a part of a search and rescue mission including lifeboats and helicopters. This UAV was the first iteration of three UAVs which will be designed, optimized, built, flown as a part of the DECODE research project. Figure 1. shows the general design of the first UAV. An associated workflow for optimization of the design and use of this system was also constructed.

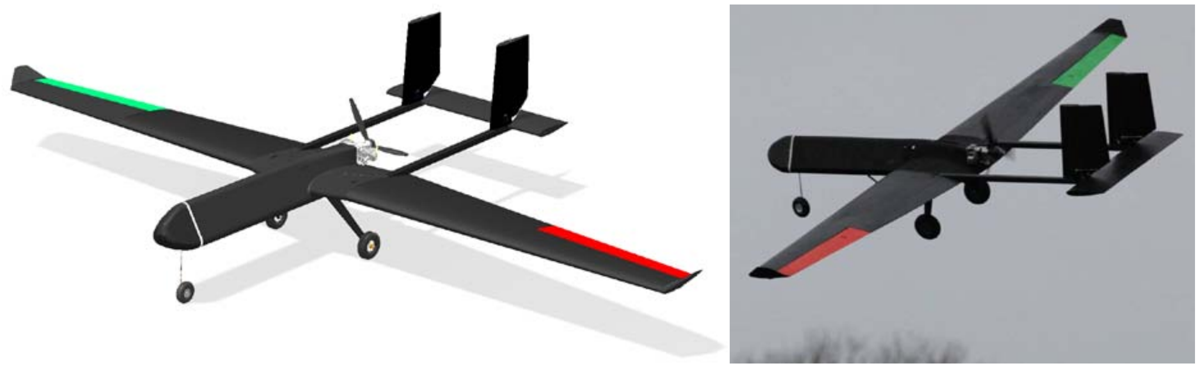

Figure 1. The DECODE UAV system discussed in the case study as designed and in flight.

The UAV design process described includes the concept and embodiment design, construction, flight testing and recording the findings for use in the next design iteration. It was a new design, with no reuse of any in-house designed parts from previous design iterations. The Solidworks 2009 CAD program was used for the geometry design. The design rationale was captured in Compendium, using a shared database for all the team members. The 10 person team working on various tasks in this project all had different roles in the design process. Four distinct working groups can be distinguished: management and advisory team (3 persons), aircraft design team (4 persons), analysis software team (2 persons), and mission simulation (1 person). All team members had access to all the rationale and could edit all of it, including map and nodes created by others, though this was rare in practice. Multiple designers editing the same map, either simultaneously or consecutively, during collaborative design processes did occur.

The most complex single part in the aircraft, shown in Figure 2, which incorporates the rear fuselage section, engine mount and wing box will be the main part discussed in this case study. This is a structurally critical part, which has a large number of interfaces with other parts. This part was made in one piece using rapid manufacturing in SLS nylon. It measures 550 by 430 by 160 mm and weighs 720 grams. The high production costs of SLS are offset by the absence of any tooling, construction or assembly man-hours costs and the high level of design flexibility (there are few geometry constraints with this manufacturing process). There was little previous experience with designing for the SLS nylon manufacturing process in the design team, but substantial experience with a similar rapid manufacturing technique: fused deposition modeling (FDM).

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[1] See www.soton.ac.uk/decode

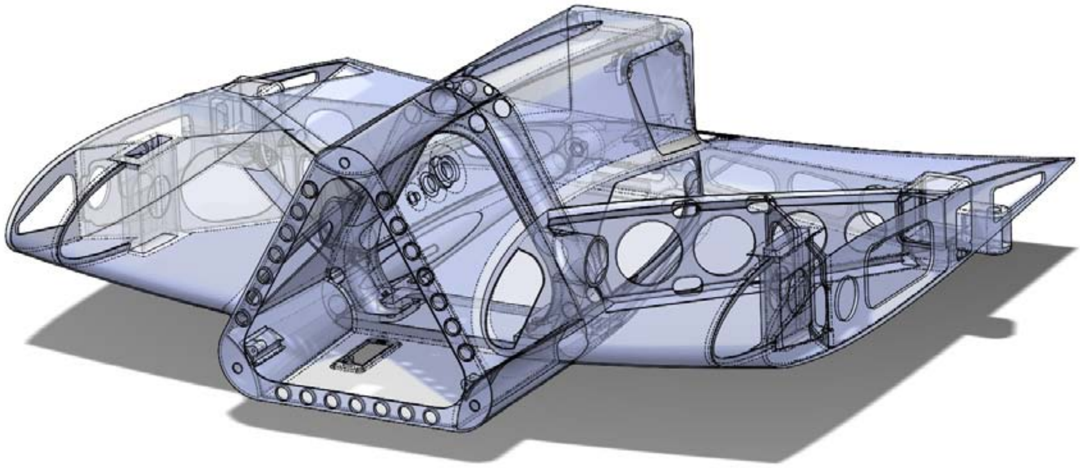

Figure 2. Rear fuselage showing internal structures

As the part is made directly from the CAD geometry, the quality of the CAD geometry has to be very high and all the detail has to be present in the geometry, as even very small gaps or errors in the design will be reproduced in the physical geometry. Our case study will use this part as an example of a complex embodiment design task.

2. OBSERVATIONS ON CAPTURE OF DESIGN RATIONALE.

The tool used in this case study was Compendium; [2] see Figure 3. for a typical rationale map.

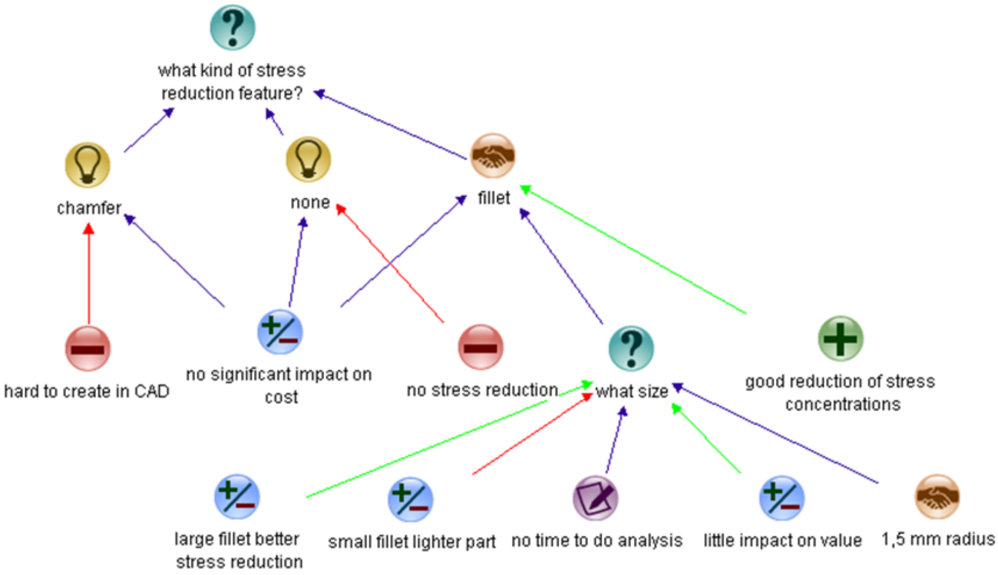

Figure 3. Typical Compendium design rationale map

To measure the capture of rationale it is necessary to first define a metric to capture the quantity of rationale. The basic unit which is manipulated during design rational capture is the *node:* Issues, Answers and Arguments are all graphically represented as nodes. Arrows can connect nodes to give structure and hierarchy to a decision process. One or more decision processes are contained in a map, which is a node in itself and can be placed in other maps as a node. The decision to record the number of nodes created by the designers rather than the number of issues, arrows or maps was taken for two reasons: firstly because the creation of a node and its creation time are recorded unambiguously by Compendium, and secondly because it is arguably the most objective measure of rationale capture; Maps can be empty and Issues can be without Answers. Counting the nodes created does not consider the quality of the design rationale captured however. Compendium allows node transclusion; the occurrence of one node in more than one map. In this article the occurrence of nodes is counted, so transcluded nodes will be counted multiple times: 1716 nodes occurences were created between the 6th of March 2010 and the 21st of January 2011, for 1645 unique nodes. Nodes which were deleted are not counted. Figure 4. shows the number of rationale nodes captured by node type. The following node types were used: Maps, which contain the rationale; Questions, the Issue being discussed; Positions, which indicate alternatives; Pros contain favourable features of an option; Cons, the negative; Arguments, the neutral; References link to external information; Notes contain text; Decisions indicate which alternative was chosen; Lists contain lists of information or nodes.

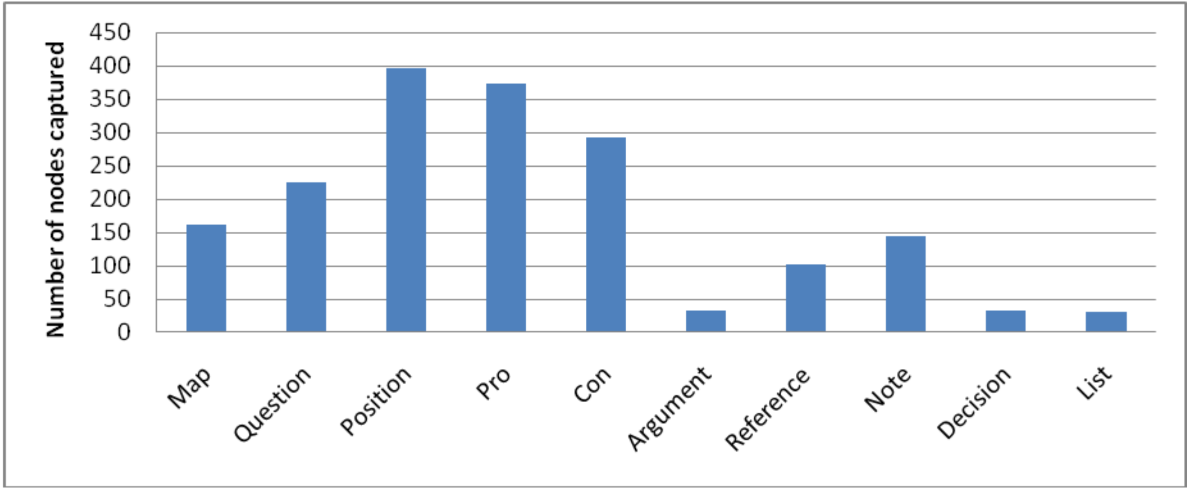

Figure 4. Rationale capture by node type

The relative absence of Decision nodes can be explained by the lack of a formalized system to transform questions where sufficient alternatives and evidence had been examined into decisions. The contribution of nodes per person ranges from 2 to 839 nodes. In general those with a management oriented task contributed fewer nodes than those with engineering or software design tasks. Node creation during the project is shown in Figure 5.

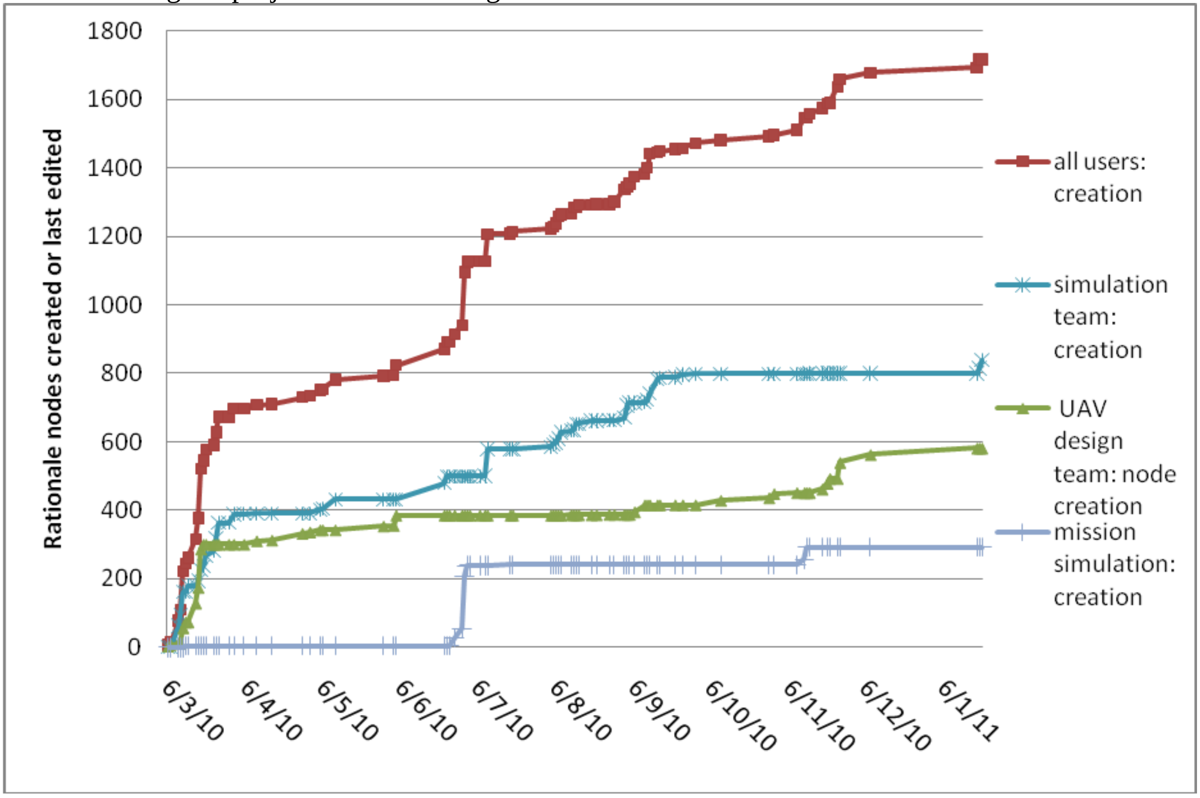

Figure 5. Design rationale captured during the project

It becomes clear that there is a substantial variation of rationale capture with time, especially when the rationale capture per team is considered. The rationale capture by the management team is not shown as the total number of rationale nodes created, less than 50, was very low. The mission simulation study had a later start, June 2010, explaining the slow start of rationale capture. A common pattern in all three teams is that the rationale capture has an intense start, often followed by a period where no rationale is captured and then renewed period of capture at the end of the process. When we consider the rationale of the UAV design team these points in the rationale capture process can be seen to coincide quite clearly with key points in the design process. Figure 6. shows the design rationale capture by members of the aircraft design team. It is clear that very little rationale was captured during the embodiment design phase, even though a substantial amount was captured during the concept design stage. A similar drop in rationale capture during embodiment design was previously mentioned by Eng et al. [12]. The 'node creation' curve shows the number of nodes created to date; the 'last node edit' curve shows the number of nodes unedited after the date. The vertical proximity of the 'node creation' and 'last node edit' curves show that very little of the rationale nodes were edited after their creation.

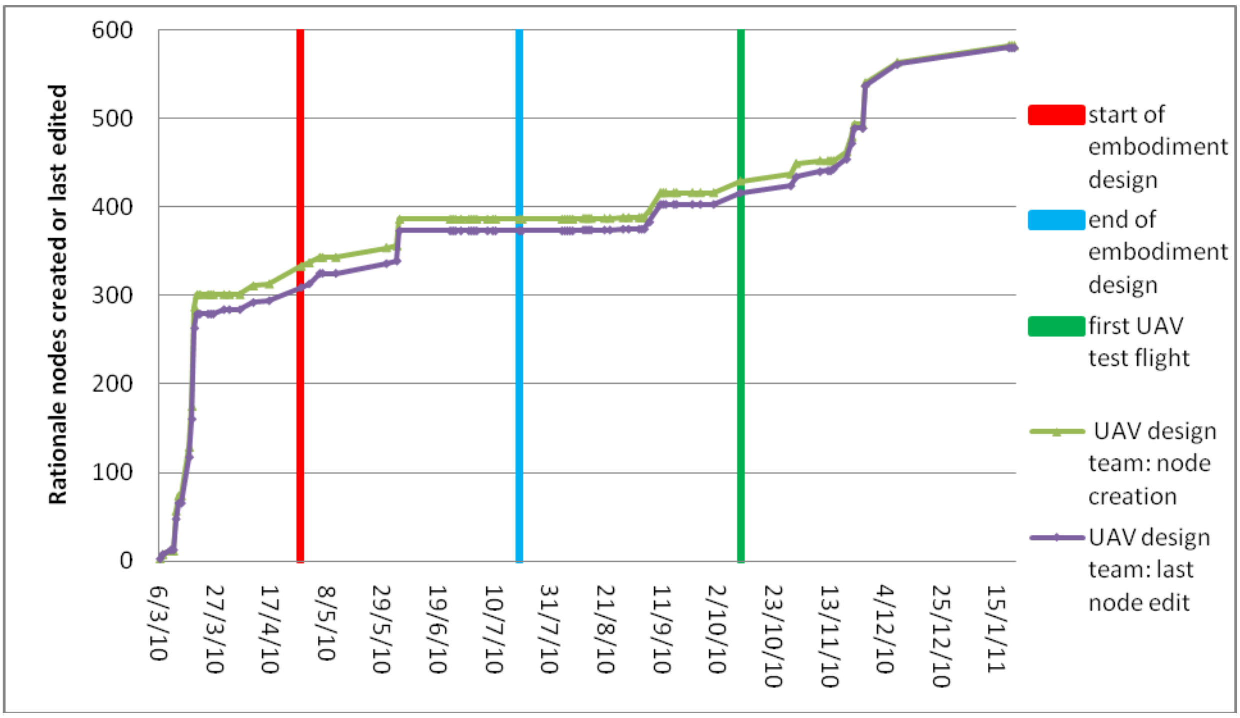

Figure 6. Quantity of design rationale captured during the design cycle.

The embodiment design started around the 28th of April 2010, which is defined here as the point where the first new design was created which was used in the aircraft. Embodiment design is considered to have finished the 19th of July, the last pre-production change to the CAD geometry. The first test flight took place on the 9th of October 2010. Weekly progress and design review meetings were used to monitor the design process and solve conflicts between the designers. During the UAV pre-flight and flight testing process there was once again an increase in design rationale capture, which can be explained by the design team revisiting the rationale and added more precise data or information gathered during the tests. However this took place in the form of adding nodes, rather than changing existing ones; the graph shows very few nodes were changed after their creation.

Why did this drop in rationale capture occur?

The design team used Compendium extensively to capture design rationale during the concept design. Why did their rationale capture drop once geometry design started? Three possible reasons for the drop in rationale capture were found:

- The important design decisions, for which it is important to capture the rationale, are identified during the concept design and their rationale is captured at this time.
- There is no automated way to link rationale to geometry, making the capture of rationale referring to a specific part/area or feature of the geometry difficult.

- The embodiment design process using a CAD program is an immersive experience. Designers are so focussed on creating and editing geometry that they are disinclined to interrupt this immersion to use other tools.

We'll consider the support for each of these three explanations for the drop in rationale capture using the rear fuselage design seen in Figure 2. as an example.

Dimensions and rationale in the CAD part.

The embodiment design of the part shown in Figure 2. took place between 28th of April and 19th of July 2010. During this period very little rationale was captured by the design team, however a substantial part of the design rationale captured during the concept design relates to features or interfaces in this part. During the embodiment design stage detailed reference geometry is created in the CAD tool and dimensions are used to define the geometry. When all the dimensions constraining the geometry are shown, as in Figure 7, their number is, perhaps, surprisingly high.

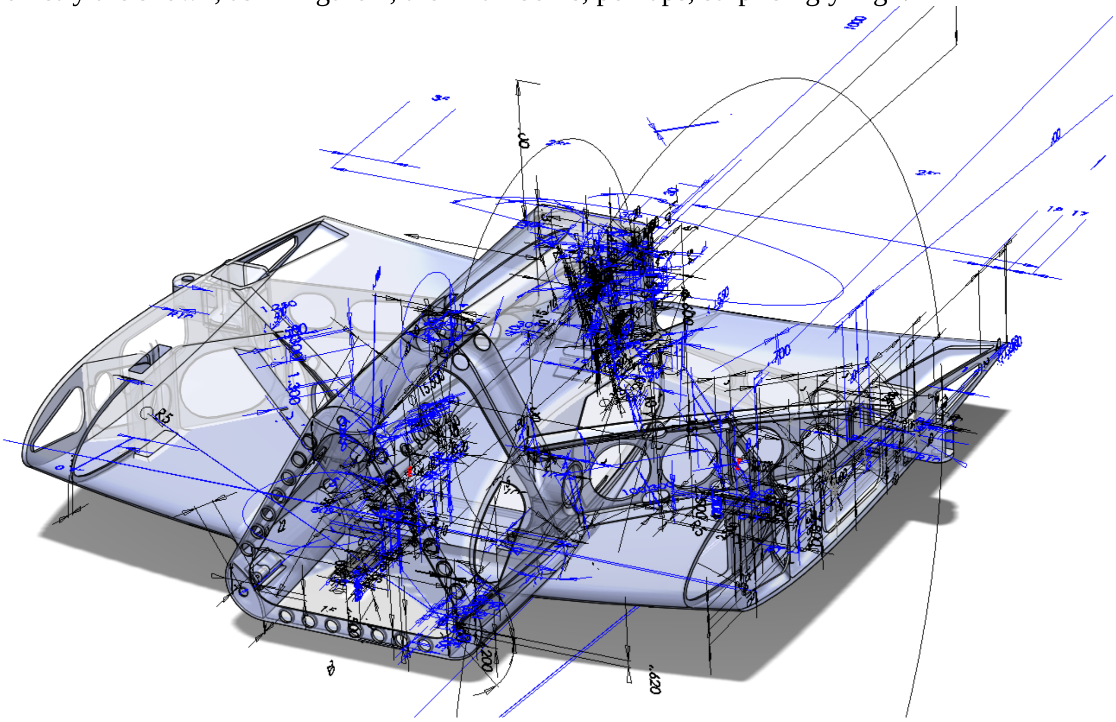

Figure 7. Dimensions in a single part.

The CAD part in Figure 7. contains 486 dimensions while the concept design contains 21 parameters relating to this part. The concept design only defines 4% of the total parameters, the rest were defined during the embodiment design phase. Few of these dimensions will be key design drivers, in the sense that changing them has a large and direct influence on aircraft performance. Generally the key parameters, such as wing span or wing chord, have been recognized early in the design process and have been defined or outlined during the concept design stage.

Rationale is created during concept design

During the concept design stage rationale was created and captured for the obvious issues in the design, such as interfaces with other parts, however very little rationale was created for the internal structure, which largely evolved during embodiment design. During the concept design phase rationale can only be captured for decisions which can be taken at that time; the decisions for issues which are known to exist. During embodiment design the geometrical reality of the part becomes apparent and problems, such as overcrowding of functionality in a limited space, become apparent. Every dimension added to the design is an explicit decision. The presence of 486 dimensions in this part shows a lot of decision rationale has not been captured given that only 600 nodes have been captured by the design team for the entire airframe.

Inability to link CAD geometry to captured rationale

If the designer would want to capture as much of the design rationale as possible, it would be necessary to create a rationale map for every new dimension and decision in the design. Suppose the designer is implementing a stress reduction feature in the corner between two extrusions. An example rationale map for this decision process is shown in Figure 3. The designer identifies three options: no stress relief, a fillet, or a chamfer. As already mentioned, the production method of the part is Selective Laser Sintered (SLS) Nylon. Because the rapid manufacturing method is additive the extra complexity added as a result of the newly introduced stress reduction feature has no impact on production cost other than through any extra weight of material used [16]. The decision is made to create a fillet. This creates a new issue: what radius should the fillet be? There are two conflicting issues here: The smaller the fillet the lighter the total part, but the higher the stress concentration in the intersection. A very large fillet would be heavier than the extrusion it supports, which may not increase the value of the design. Currently it is hard to capture this rationale as there are 59 “fillet” features in the geometry of the part and each of these features fillet multiple edges. The rationale for other fillets might be similar or different but how can we quickly and with certainty ascertain that it is indeed this fillet the map refers to? Nor is it appropriate to copy many identical rationales for similar decisions. We believe that one of the main reasons why rationale is not recorded during detail design is that there is no simple and quick way for the designer to link parameters in his CAD design to the relevant design rationale. The designer could create one rationale map for the standard decision and then capture the specific rationale of exceptions.

CAD design is an immersive experience

During the embodiment design stage a large portion of the designer’s time is spent manipulating geometry using a CAD engine. Often designers will become completely absorbed in this task. Is it bad to disturb them, by requiring them to step away from the CAD program and capture the design rationale? During a systematic design process such as described by Pahl et al. [17] or Pugh [18] the entirety of the concept design stage is completed before starting embodiment design and the number of iterations between these stages is kept to a minimum. In practice design is not always systematic, and frequent alternations between detail and concept design do occur, especially with experienced designers [19]. As these designers switch several times per hour between concept design and detail design it seems continuous interaction with the CAD program is not a requirement for effective design.

Is it economic to capture more of the design rationale during geometry design?

Capturing rationale is costly, and the reward is uncertain. It is hard to create models that take into account a possible future reward for capturing the rationale now due to the uncertainty of reuse of the parts and rationale. As rationale can help preparing documentation or partially replace text based documentation [12], projects which have high documentation requirements can support a higher rationale capture cost. Reducing the cost of capturing rationale will make it an economical in a greater number of situations. If the designer is obliged to capture rationale for every parameter in the detailed geometry design and creating this rationale would take, on average, 10 minutes per parameter, the total investment for the part in Figure 7. would be 75 hours of designer time, a very significant (30%) addition to the product design time.

Improving the design reviews using design rationale.

Preproduction design reviews or audit processes are commonly used: for example as NASA [20]. There is no purpose to a design review if there is no opportunity for the reviewers to find error with the design: a good review process should make the design as transparent and accountable as possible. When conducting a preproduction design review of a part by examining the CAD geometry, the sheer number of parameters makes it quite hard for the reviewers to find design errors or weaknesses without the context of design rationale, either as narrated by a human interpreter to explain decisions or in the form of a captured rationale. The value of having easily accessible design rationale during a design review process would be high. In this context the ability to check the rationale for consistency would be valuable; the DRed rationale editor includes a feature [10] to check the rationale for logical consistency of the arrangements of element types used in the decision. The less strictly imposed syntax of design rationale captured in Compendium makes the automation of rationale syntax checking difficult.

3. PROPOSED SOLUTION: INTEGRATION OF CAD AND RATIONALE TOOLS

Many decisions are made during embodiment design which are not well captured in the rationale tool. Reducing the cost of rationale capture could be achieved by embedding the rationale editor in the CAD program. This is not a new concept: a NASA requirements paper [21] calls for a 'Design rationale capture tool' states that this tool should be embed in commonly used design tools. Lee [1] also identifies this need. Boujut [22] describes an annotation system linking to the visual part of the CAD design. Integration of design rationale programmes with other design programs is often discussed [1], [21] and generally viewed favourably but not often put into practice. Bracewell *et al.* mention the integration of DRed with CAD software as possible future work [9] but this remains unpublished. Bracewell *et al.* do describe the integration of the DRed programme with various Microsoft office applications [23]: The ability to link to Excel gives the option of controlling CAD geometry from the Rationale editor by means of the parametric design functionalities natively present in many CAD systems which store parameters in Excel files. Mix *et al.* [24] describe method where an audio communication and capture utility, Skype, is integrated into the CAD tool (NX 6) and calls to colleagues made during the design process, as well as narrative audio files are recorded into the rationale, as well as the CAD actions performed during this time. The difficulty would be finding the rationale for a certain decision between all these audio files. Improving the connection between rationale and the design, the barrier for its capture and subsequent use is lowered in two ways: the time it takes to capture rationale is reduced as it's not necessary to switch programs, and the connection of parameter and rationale allows quick retrieval of associated rationale.

3.1 Linking Rationale to geometry

Solidworks has an Application Programming Interface (API) which can be used to customize the software. A DECODE research vision is to embed Compendium inside Solidworks as in Figure 8. The C# program used as the API will directly edit the SQL database which stores the compendium maps, so new nodes can be created for dimensions in Solidworks through the API. These Compendium nodes can then be edited normally in Compendium. This will allow rationale captured during concept design to be accessed and augmented during the geometry design stage.

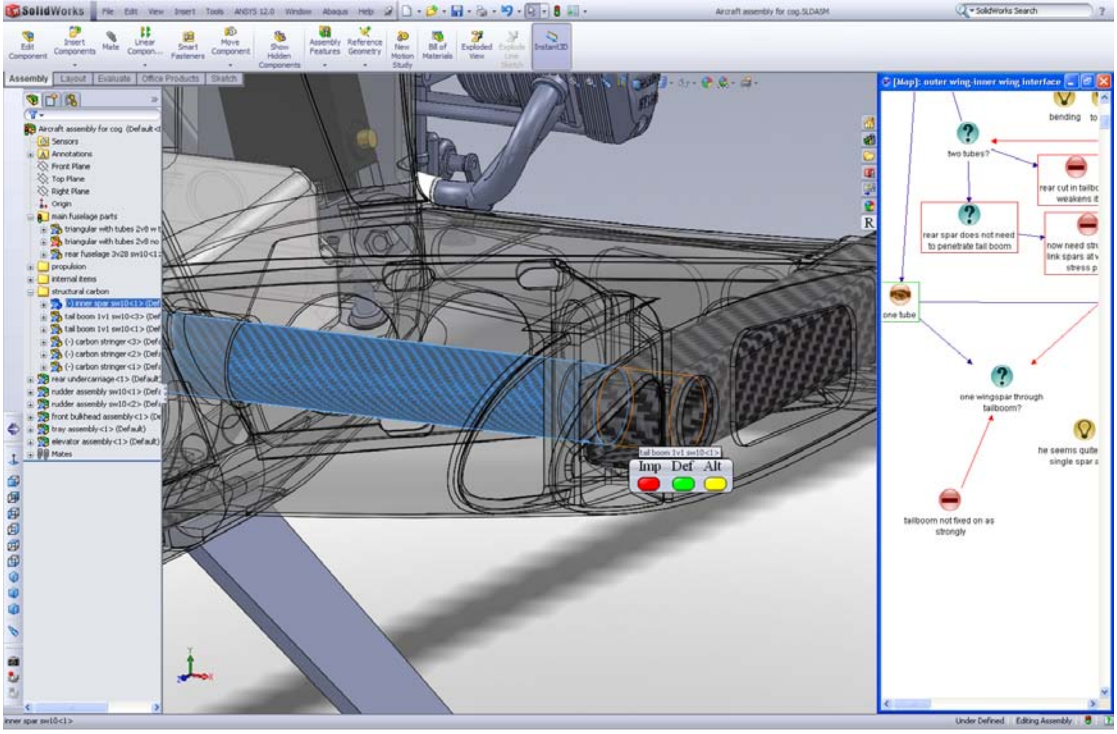

Figure 8. Compendium embedded in Solidworks: a concept.

4. DISCUSSION AND CONCLUSIONS

This case study confirms Eng's [12] findings concerning the drop of rationale capture during embodiment design. "*Why should the engineering community be afflicted with yet another software tool?*"[12]. Rather than creating another rationale capture tool, the proposed integration of readily available tools should reduce the design decision support gap which currently exists. The implementation of a connection between CAD geometry and design rationale would be the most important step for testing the hypothesis that the reduction in design rationale during detail design is due to insufficient support for parameter-rationale connections. We will then use the integrated rationale system during the design of a second DECODE UAV system, so that the difference in quantity of the design rationale captured during the geometry creation can be compared.

Conclusions

During the concept design stage a large quantity of design rationale is captured, however during the embodiment design stage there was a marked reduction in the capture of rationale. Two possible causes are identified:

- The designer has little incentive for creating rationale during the detail design stage, as it is difficult to connect parameters with the relevant rationale;
- Important issues were identified during concept design, making rationale capture during detail design redundant.

The work presented here proposes to improve the relevance of rationale for CAD geometry and vice versa, reducing the cost of the creating of rationale graphs during the detail design stage by means of the creation of links between the rationale and the CAD geometry. The increased level of integration allows the capture of rationale which remains relevant even during the detail design stage. Further investigation is required establish whether these new additions to the spectrum of design tools are sufficient to empower designers to capture meaningful rationale during detail design.

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