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Model-based information navigation for engineering documents

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ABSTRACT

Engineering and the manner in which engineers think is largely visual and functional, and yet engineers are typically provided with search engines that are text-based. While software based on a visual and functional ethos exist (CAD for example), when searching for information engineers are still required to enter a text query into a search box. This process holds potential incompatibilities both with the nature of the data (i.e. 3D models) and with the way in which engineers think and work. Consequentially, the proposition tested in this paper is that a model-based approach to information access, i.e. a representation of an organisations information around a model of an artefact i.e. CAD model, can improve engineering information retrieval.

In an A-B test with a traditional text-based search engine, and using study questions derived from real-world information seeking scenarios based on the activities of a world-leading aircraft manufacturer, the results presented in this paper suggest that there is merit to such an approach. Specifically, this paper shows that there is no significant difference in time to complete a search between a model-based and text-based interfaces in spite of the addition of a new stage in the search process (navigating a 3D model); that the system structure of the model-based interface allows for non-text based documents to be indexed, making up for the inherent limitations in traditional text-based search; and that participants enjoy using the model-based interface and find it intuitive, easy and simple to use. Further, this paper also finds that those with more experience/familiar with the product structure and those in managerial positions are more likely to find information using a model-based interface that those who are not, who perform better using a text-based interface.

1. Introduction

Knowledge, information, and data are widely considered to be an organisation's greatest asset and as such, the effective capture, use and re-use of this asset is simply deemed as good practice [1]. The growth of knowledge management activities is one response to this ethos [2], and includes activities, systems, and methodologies aimed at the capture, storage and dissemination of knowledge, information, and data such that the members of an organisation are as well informed as they can be [3–6].

Information dissemination, the means of communicating an organisations' information to its personnel is central to an effective knowledge management strategy; if one cannot find and/or access information then both the individual and the organisation cannot benefit from it. A primary means of delivering this is through Intranet or enterprise search engines [7]. Internet search engines touch most our lives with the major search providers of Google and Microsoft seemingly becoming the doorways into humanity's data, information, and knowledge. Within organisations however, enterprise search engines are often found lacking [8,9]. There is then a disconnect between the advances of Internet search technology and the knowledge management needs of organisations and this is particularly true for engineering organisations [10]. It is to this field that this paper contributes.

While building a search engine is largely an effort in text/metadata analysis and indexing [11], another aspect to the system is the user interface [12]. Engineers are said to think visually and func-

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0166-3615/

tionally [13] and yet they are largely provided with search engines that are text-based. Such systems require the user to enter a text query into a search box. A textual list is returned to the user who must then evaluate the list to determine the validity of each result. Examples where search does not rely on this type of user interface include virtual map applications such as Google Maps[1] and Flickr.[2] While these offer the option to enter text queries, both use the context of the information in question (geography) to display the results over a map. This provides the user with a context beyond that provided by textual lists, against which they can evaluate results.

Engineering and the manner in which engineers think is largely visual and functional and this can be seen in the means by which engineers communicate through boundary objects [14], including technical drawings, sketches, CAD and three-dimensional models. As these forms of information and the manner in which an engineer thinks is visual and functional, then it stands to reason that engineering search may benefit from a search engine that capitalises on the types of representations used by engineers. It follows that the proposition of this paper is that a model-based approach to information access, i.e. a representation of an organisations information around a model of an artefact that the engineer uses, can improve engineering information retrieval (see Fig. 1).

Given this proposition, the contribution of this paper is an evaluation of model-based information navigation against the more traditional means of information search. The ultimate goal being to determine whether such an approach to information retrieval merits future research efforts and real-world implementations. To determine this, this paper presents a rigorous real-world A-B test using trainee engineers and a traditional text-based search system (A) and a model-based search system/information navigation system (B). The paper begins with a summary of related literature followed by a discussion of the experimental platform and methodology. Results are then presented alongside a discussion of key findings and industrial implications.

2. Background

A model-based approach to information retrieval transcends a number of interrelated fields such as information search, engineering information search, model-based approaches to engineering, and model-based information navigation.

2.1. Information search

Whether Internet or Intranet the basic fundamentals of search are similar and date back to finding information in library catalogues [15]. The process of building a basic search engine is then relatively straight forward [16]. Starting with a corpus of documents, a collection of technical reports or every website on the Internet for example. The entire system operates by matching users' search queries to the words contained within the documents in the corpus. At the point when a user enters a search query, the search engine does not trawl through every document in the corpus, that would be highly inefficient and take a long time. The corpus is pre-processed, and stored as an index, with the inverted index being one of the most common and efficient types [16].

The easiest way to think of the inverted index is as two table columns, the first column being the *dictionary*, and the second column being the *postings*. The *dictionary* is formed of every word in every document in the corpus, and the *posting* is the list of every document containing that word. So when the user enters a search query, the search engine is merely scrolling though the first column of the index, and returning the second column. This pre-processing allows the big Internet search engines are able to return hundreds of thousands of results, in fractions of a second.

While building a basic search engine is this simple, the challenges begin when one wants to build a really good search engine. What happens if the user miss-spells the query, when the user enters the query *jaguar*, do they mean the animal or the car company (homonym problem)? when the user enters the query '*air plane*' but the corpus only uses the term '*aeroplane*' (synonym problem)?, and are *USA*, *U.S.A*, and *United States of America* all the same (abbreviation problem)? All this is before one considers the order in which results are presented. Google's dominance was built on the PageRank algorithm [17], an algorithm that ordered results based on the number of links to each website.

Manning et al. [11] present solutions to these problems and many more, however, the challenge of search is still an area of great academic interest. Techniques of ontology [18] and semantic search [19], personalised search [20], structured-document retrieval [21], and graph-based search [22] are all examples of techniques aimed at structuring collections of documents such that when a user enters a query, the relevant documents are retrieved and returned. As a research field then, information search through search engines is one where the basics are well understood, however there are still many challenges in implementing and improving performance.

2.2. Engineering information search

The concurrent nature with which engineering organisations operate results in teams of specialist engineers dispersed both in terms of geography and specialisms [23]. This approach to management impacts the types of information generated, the format in which it is captured, the language used, and the domain specific terminology used, which ultimately results in collections of documents that are difficult to disseminate. For example, an aerodynamics team are concerned with the external surface of an aircraft wing while a structural engineer will be concerned with the internal ribs, the electrical team will want to run cables down the wing, the hydraulics team will want to run hydraulic pipes, and so on and so on. Each of these teams considers the wing within the context of their own specific domains and yet the outputs from each team can directly impact the other teams. The Airbus Group's response to these challenges places the three-dimensional model at the heart of the project management process [24].

This is why information dissemination is important, it is key to enabling teams to work both independently in their own specific domain (multidisciplinary), and together as the wider team (interdisciplinary). While product life-cycle management systems attempt to address this, organisations still rely on search engines, which are often found lacking. Hawking [9] described the challenges of enterprise search in general, with Stocker et al. [10] providing a more engineering specific review. In their study, Stocker et al. introduced Microsoft SharePoint 2013 into two engineering research and development departments (automotive and rail) and found performance issues relating to: users, documents and the search engine itself. Users were said to have had problems formulating queries and tagging documents with meta-data when uploading them to the system. Documents were said to be to inconsistent in content and structure. SharePoint itself was said to rank search results misleadingly, an example of this is ranking by popularity – users search for the latest/current report however, the previous quarters report will always rank higher by popularity based on the length of time that the document has existed/the number of times that it had been accessed.

Mukherjee et al. [8] explored the possible reasons behind the difficulty in delivering enterprise search when compared to inter-

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[1] maps.google.com. Last visited: 2019/08/15.

[2] flickr.com/map. Last visited: 2019/08/15.

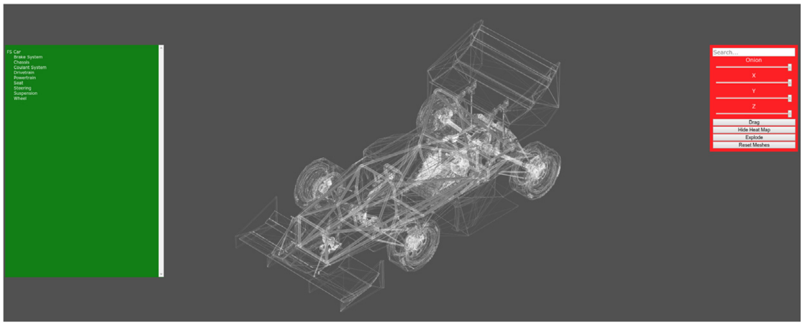


Fig. 1. A model-based information navigation user interface.

net search. Many enterprise search systems are based on Internet technologies and processes, the Internet however, is constructed such that: (1) when someone creates a website, they do so wanting search engines to index their content and so make efforts to ensure this is possible; (2) HTML, the language of the Internet, is structured such that website content is machine-readable and so easy for search engines providers to catalogue.

Compare this to a finance team's quarterly reports generated in Microsoft Excel, a two-dimensional technical drawing created in AutoCAD, or some complex computational fluid dynamics analysis of the structure of the wing which are designed with other, non-search related functionality in mind. So these file formats exist for a purpose in their own rights, which do not in any way include being found on the Internet, and while meta-data is in theory a possible solution to this, it relies on every document creator in an organisation understanding what meta-data is and including it, and to be fully up-to-date with all the domain specific terminology used throughout the entire organisation. In spite of this, it is Internet technology that many enterprise systems rely on.

There have been attempts to improve Intranet/enterprise search, the Airbus Wing In-Service team themselves being one example, through supporting the research and development of a custom context aware search engine called Daedalus [25]. The novelty in Daedalus is in its use of ontological data structures to expand and reinforce search queries within an engineering domain and the hierarchical structure of the aircraft. For example, documents relating to an aileron also relate to the wing as a whole, Daedalus is able to capture and use this relationship to return more relevant results.

The context aware approach aims to overcome some of the limitations of Intranet/enterprise search engines: a reliance on a common lexicon and naming convention between teams, departments and individuals. This is achieved through a textual representation of the physical structure of the product, however, search queries are still text-based. This text-based nature of traditional search is counter to the manner in which research shows engineers communicate: they do so using visual representations and boundary objects [14], in line with the visual and functional nature in which engineers think [13]. It is this disparity that is explored in this paper: does a visual representation of an engineering artefact, i.e. a model-based approach, aid information retrieval. So called model-based approaches can be seen throughout engineering and so, can it make a difference in search?

2.3. Model-based approaches to engineering

Model-based approaches to engineering are not a new concept. ISO 16792:2015 includes the international standards for model-based definition, an approach to product data management where a three-dimensional model of the product is annotated with specific pieces of information, within the CAD package. Examples of data include: dimensions, tolerances, and general notes/design rationale [26,27]. Engineers are able to access this data in an intuitive manner – through a three-dimensional representation of the product.

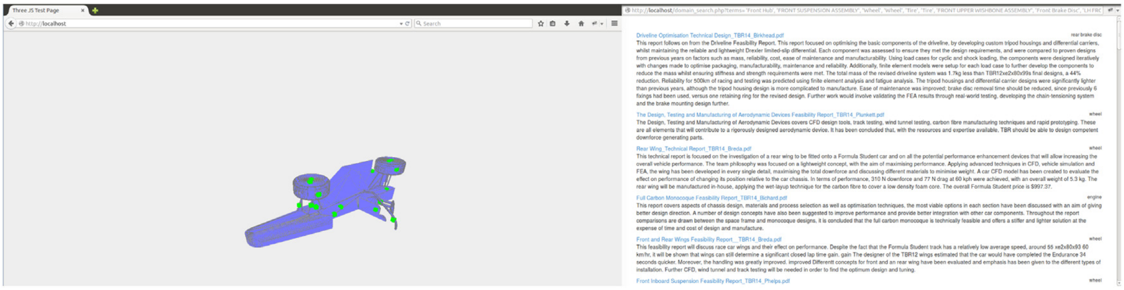
The data contained within model-based definitions are short snippets rather than complete documents such as technical reports. Design rationale may, for example, be a few concise sentences of text rather than the full requirements document produced in conjunction with the customer. While the appropriateness of the amount of data/information is dependent on the needs of the end user, model-based definitions do not yet support the wider needs of the whole organisation, i.e. those occasions where the user turns to the Intranet/enterprise search engine. Document search via a model-based user interface (or model-based information navigation) then provides both the means to perform document search through the same intuitive means as model-based definitions.

2.4. Model-based information navigation

If a model-based approach in engineering involves the access of information within a three-dimensional representation of the product, information navigation is the process of navigating that three-dimensional space to find that information. The Springer Encyclopedia of Database Systems [28] defines the term *information navigation* is a metaphor stemming from geographical navigation with people accessing chunks of digital information in a "*goal-directed way*". Within a model-based approach to information navigation, the three-dimensional representation of the product components and systems/subsystems effectively chunk information, the user then manipulates and moves within the that three-dimensional virtual environment to find information. This is in contrast to an information search, where users generate relevant terms and use them to query a search index. The three-dimensional model acts as a map to guide users towards their information goal.

An early study into the feasibility of a model-based approach to information retrieval [29] determined the web-based technology, data structure, and appropriate visualisation techniques. At the time referred to as *artefact-based information navigation* (see Fig. 2), the approach built on research that visualised a corpus documents in three-dimensional space as points-of-interest [30] situated around a three-dimensional model of the product. A results list was filtered based on the points-of-interest visible as the user navigated the virtual environment. The paper found however that the user interface became visually cluttered quickly and linking documents at a component level was more appropriate. This led to further work in the area of visually representing engineering information in model-based virtual environments including the design of a number of visual-information-objects [31]; effectively visual markers used to identify the location of information (see Fig. 3).

The positioning of information in the model-based virtual environment raises further challenges of where do documents belong, i.e. when a user clicks on the front left brake pad, what documents are returned? While classical document indexing techniques (such



http://localhost/domain_search.php?terms= 'Front Hub', 'FRONT SUSPENSION ASSEMBLY', 'Wheel', 'Wheel', 'Tire', 'Tire', 'FRONT UPPER WISHBONE ASSEMBLY', 'Front Brake Disc', 'LH FRC

Driveline Optimisation Technical Design_TBR14_Birkhead.pdf — rear brake disc

This report follows on from the Driveline Feasibility Report. This report focused on optimising the basic components of the driveline, by developing custom tripod housings and differential carriers, whilst maintaining the reliable and lightweight Drexler limited-slip differential. Each component was assessed to ensure they met the design requirements, and were compared to proven designs from previous years on factors such as mass, reliability, cost, ease of maintenance and manufacturability. Using load cases for cyclic and shock loading, the components were designed iteratively with changes made to optimise packaging, manufacturability, maintenance and reliability. Additionally, finite element models were setup for each load case to further develop the components to reduce the mass whilst ensuring stiffness and strength requirements were met. The total mass of the revised driveline system was 1.7kg less than TBR12xe2x80x99s final designs, a 44% reduction. Reliability for 500km of racing and testing was predicted using finite element analysis and fatigue analysis. The tripod housings and differential carrier designs were significantly lighter than previous years, although the tripod housing design is more complicated to manufacture. Ease of maintenance was improved; brake disc removal time should be reduced, since previously 6 fixings had been used, versus one retaining ring for the revised design. Further work would involve validating the FEA results through real-world testing, developing the chain-tensioning system and the brake mounting design further.

The Design, Testing and Manufacturing of Aerodynamic Devices Feasibility Report_TBR14_Plunkett.pdf — wheel

The Design, Testing and Manufacturing of Aerodynamic Devices covers CFD design tools, track testing, wind tunnel testing, carbon fibre manufacturing techniques and rapid prototyping. These are all elements that will contribute to a rigorously designed aerodynamic device. It has been concluded that, with the resources and expertise available, TBR should be able to design competent downforce generating parts.

Rear Wing_Technical Report_TBR14_Breda.pdf — wheel

This technical report is focused on the investigation of a rear wing to be fitted onto a Formula Student car and on all the potential performance enhancement devices that will allow increasing the overall vehicle performance. The team philosophy was focused on a lightweight concept, with the aim of maximising performance. Applying advanced techniques in CFD, vehicle simulation and FEA, the wing has been developed in every single detail, maximising the total downforce and discussing different materials to minimise weight. A car CFD model has been created to evaluate the effect on performance of changing its position relative to the car chassis. In terms of performance, 310 N downforce and 77 N drag at 60 kph were achieved, with an overall weight of 5.3 kg. The rear wing will be manufactured in-house, applying the wet-layup technique for the carbon fibre to cover a low density foam core. The overall Formula Student price is $997.37.

Full Carbon Monocoque Feasibility Report_TBR14_Bichard.pdf — engine

This report covers aspects of chassis design, materials and process selection as well as optimisation techniques, the most viable options in each section have been discussed with an aim of giving better design direction. A number of design concepts have also been suggested to improve performance and provide better integration with other car components. Throughout the report comparisons are drawn between the space frame and monocoque designs, it is concluded that the full carbon monocoque is technically feasible and offers a stiffer and lighter solution at the expense of time and cost of design and manufacture.

Front and Rear Wings Feasibility Report__TBR14_Breda.pdf — wheel

This feasibility report will discuss race car wings and their effect on performance. Despite the fact that the Formula Student track has a relatively low average speed, around 55 xe2x80x93 60 km/hr, it will be shown that wings can still determine a significant closed lap time gain. gain The designer of the TBR12 wings estimated that the car would have completed the Endurance 34 seconds quicker. Moreover, the handling was greatly improved. improved Differentt concepts for front and an rear wing have been evaluated and emphasis has been given to the different types of installation. Further CFD, wind tunnel and track testing will be needed in order to find the optimum design and tuning.

Front Inboard Suspension Feasibility Report_TBR14_Phelps.pdf — wheel

Fig. 2. An early model-based information navigation system prototype.

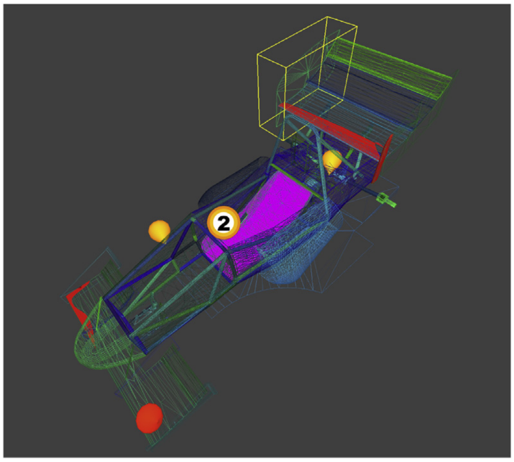


Fig. 3. Example of methods for displaying information within a model-based virtual environment using visual information objects.

as those applied in traditional search engines) can be applied, there is also an opportunity to improve on these techniques through document classification [32].

While there is work being published in relation to model-based information navigation [29,31], it has not yet been determined whether there is any merit in such an approach. This is addressed in this paper, with a direct comparison between a model-based approach and a traditional text-based approach to information retrieval and document search, the effect of a model-based approach is determined.

3. Experimental platform

The experimental platform developed for this paper was based on the documents, files and participants from the IMechE Formula Student[3] teams at the University of Bristol and the University of Bath. From whom the documents used were obtained. These include 504 Formula Student End of year reports from the University of Bristol and the University of Bath, Formula Student Guideline documents issued by IMechE Formula Student Organisers, and a small number of digital textbooks. These were all documents currently being used by the Bristol and Bath Formula Student teams and were stored in pdf format. The three-dimensional CAD model used was obtained from the team at the University of Bristol. The CAD model was first converted to an STL (stereolithography file format describing the surface geometry of a three-dimensional object) file before being compressed using OpenCTM[4] into the CTM (Compressed Triangle Mesh) file format, a compact binary format for storing triangular meshes.

In terms of the technology used for both model-based and text-based user interfaces, a HTML website hosted on an Apache web-server running on Linux was used. The index, images, documents and three-dimensional models were all stored on the web-server and accessed using PHP. The three-dimensional visualisations of the model-based interface were constructed on the three.js library.[5] Appendix A.1 shows how the text-based interface appeared to the participants. Appendix A.2 shows how the model-based interface appeared to the participants.

3.1. Text-based TF-IDF search engine

Term frequency–inverted document frequency (TF-IDF) is a corpus linguistics technique for measuring the relative importance of terms within a corpus (D) and is widely used in search engines [11] and as such, forms the basis of this study. It is a combination of two measures, the term frequency (*tf*) and the inverse document frequency (*idf*). The term frequency is a count of the occurrence of term t in document d (Eq. (1)). The inverse document frequency is the natural log of the total number of documents (N) divided by the number of documents containing the term t (Eq. (2)). The *tf-idf* is the dot product of the two measures (Eq. (3)).

$$tf(t,d) = f_{t,d} \tag{1}$$

$$idf(t,D) = \log(\frac{N}{|(d \in D : t \in d)|}) \tag{2}$$

$$tf - idf(t,d,D) = tf(t,d) \cdot idf(t,D) \tag{3}$$

Ranking results by the *tf-idf* is a matter of extracting those documents containing the term(s) and comparing the term weights. Those most similar to the query are ranked higher.

Fig. 4 shows the method used for constructing the TF-IDF search engine and to align the implementation to the theory, (D) was the 504 Formula Student documents provided by the Formula Student teams at the University of Bristol and the University of Bath. (d) were the individual documents in the corpus (D). (t) were the individual terms extracted from each of the documents (d) using the technique of tokenisation [11]. The results of this processing was then stored in an index, with terms (t) forming the dictionary, and the list of paired ((d), (tf-idf)) for all documents containing the term forming the posting. The index was stored as a flat file on the server and made accessible to the web page via PHP calls.

3.2. Model-based information navigation

Creating the model-based information navigation system comprised of two parts: constructing the model-based index and

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[3] https://www.imeche.org/events/formula-student. Last Visited: 2019-11-28.

[4] http://openctm.sourceforge.net/. Last visited: 2019-11-28.

[5] https://threejs.org/. Last visited: 2019-11-28.

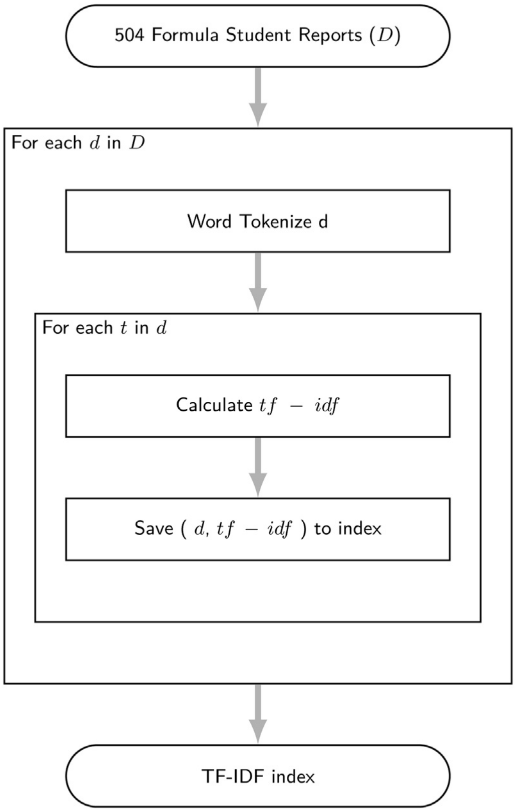


Fig. 4. Methodology diagrams showing the process of constructing the TF-IDF search engine.

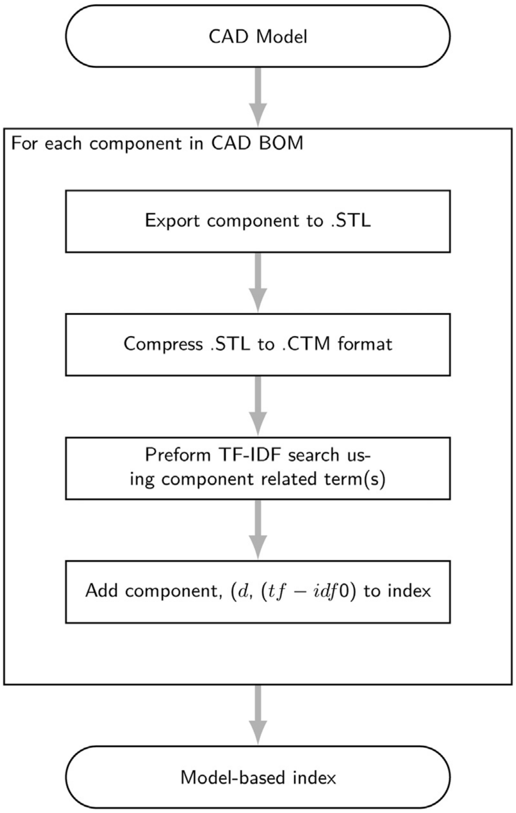


Fig. 5. Methodology diagrams showing the process of constructing the model-based search index.

constructing the user interface. Fig. 5 shows the process diagram for creating the model-based index. The first stage involves extracting the Formula Student racing car model from CAD in a low resolution STL file format. This was then converted to a light weight CTM format for quicker loading. For each of these components, a search was performed using terms relating to the component and the TF-IDF text-based index created in Section 3.1. For example, the term '*brake pads*' was taken from the BOM and expanded to include the supplier name and part number contained within the CAD file and budget documents relating to the brake pads. The component and retrieved files were then added to the model-based index along with the TF-IDF weights. Performing a search then involved linking the user's click on a particular component to the index entry for that component. This again relied on PHP server calls, returning a set of result that can then be presented to the user in a textual list, in a similar fashion to that of a traditional search engine.

The second part of constructing the model-based user interface focused on what the user would see, and how they would interact with the model-based environment on screen. There is a vast amount of literature on best practices in developing graphical user interfaces, and three-dimensional virtual environments, from Gestalt's principles of figure/ground [33] that provide insights for the layering of screen elements such that the user in not distracted, to the use of colour to draw focus away and towards certain screen elements [34]. The design of the model-based user interface was based on a thorough review of literature [35–39].

The model-based interface is a three-dimensional virtual environment and interacting with this involves three processes: navigation, selection and manipulation, and system control [40,41]. Navigation is how the user moves within the environment, selection and manipulation is how the user interacts with the environment (selecting objects for example), and system control is how the user interacts with the wider system (help files, save buttons, etc.). For the purpose of this study, the major focus was on navigation, and selection and manipulation with demonstrations and study organisers on hand to provide help.

The Three.js software library provides an OrbitControls class that allows the user to click and drag the environment and has the effect of 'spinning' the object at the centre of the screen. Given this in-built functionality, it was decided to allow the OrbitControls class to manage the user navigation. In terms of selection and manipulation, in line with common practice [42], a point-and-click approach was adopted to allow the users to use a mouse and click on components to perform searches and retrieve documents. In addition to this, the model-based user interface also includes the ability to navigate the product structure (at a component and system/subsystem level) using the BOM in the form of a textual list, a heat-map that colours components based on the TF-IDF score for a given text search query, document filter based on a text search query, and an 'onion peeling' technique that allowed users to peel back components in the X, Y, and Z planes, providing direct access to the internal components within the model. See Appendix A.2.

4. Methodology

The purpose of this study is to investigate the potential of a model-based approach to information retrieval. To achieve this, the model-based approach is compared to a traditional text-based search engine in an A-B test. That is, the study will centre around a traditional text-based search engine with two user interfaces, one traditional text box (A), and the other being a model-based interface (B), with variables controlled such that the substantive difference between A and B is the interface itself.

Prior to this A-B test though, it is it pertinent to understand the information needs of engineers in more detail, such that the A-B test is performed using real examples of real scenarios that engineers

Table 1
A summary of the engineering information seeking scenarios contained within 240 repair queries received by the Airbus Wing In-Service function during 2013.

ID	Information seeking scenario	Frequency
1	Analyse extend of damage	89
2	Evaluate proposed repair	117
3	Provide repair instructions	118
4	Approval for use of new material in repair	2
5	Order item	1
6	Provide technical drawing	1
7	Report manufacture issue	1
8	Approve repair	38
9	Instruct on inspection methods	1
10	Provide aerodynamics analysis	2
11	Provide information	9
12	Search for similar incident	1
13	Identify most common repair case locations over set period of times	N/A
14	Identify most common repair case types over set periods of time	N/A
15	Identify new knowledge from a seemingly unconnected past case	N/A

perform as part of their day-to-day. While the Formula Student teams are engaged in real projects, with real deadlines, outcomes and design/manufacture activities, they are also however students performing some engineering activities for the first time and as such, there is a risk this has an effect on the nature of information seeking scenarios when compared to a more real-world use-case. To mitigate this, the first subsection of this methodology outlines an approach to capture and understand the real-world engineering scenarios as performed by engineers at the Airbus Wing In-Service support team at Filton in Bristol. This team represents experienced engineers engaged in industry based engineering activities, and as such their information seeking behaviours are indicative of real-world behaviour. The second subsection of the methodology then outlines the A-B test.

4.1. Capturing information seeking scenarios and formulating the study questions

Given the real-world nature of the challenge of engineering information retrieval, efforts were made to ensure that this study was situated within a real-world context. These efforts began with the understanding of the information seeking scenarios relating to the Airbus Group's Wing In-Service team based in Filton in Bristol. The In-Service team are responsible for supporting repair and maintenance requests from customer airlines. Every repair/maintenance request generates a PDF report that documents the process, from the initial customer airline request, through to the final response. The Wing In-Service team provided a corpus of 240 reports relating to the single-isle A320 range of aircraft from the year 2013 for analysis, and it is the analysis of the purpose of these reports that forms the basis of the study questions with which the A-B test is performed.

A thematic analysis was performed on the corpus. The thematic analysis process as outlined by Braun and Clarke [43] and presented by Maguire and Delahunt [44] provides a methodical and structured approach to extracting themes from unstructured literature. The process involves six steps of analysis: become familiar with data; generate initial codes; search for themes; review themes; define themes; and write up; In the context of the work presented in this paper, the themes consist of the reoccurring high-level information seeking scenarios that Airbus engineers were asked to perform. These scenarios are shown in Table 1.

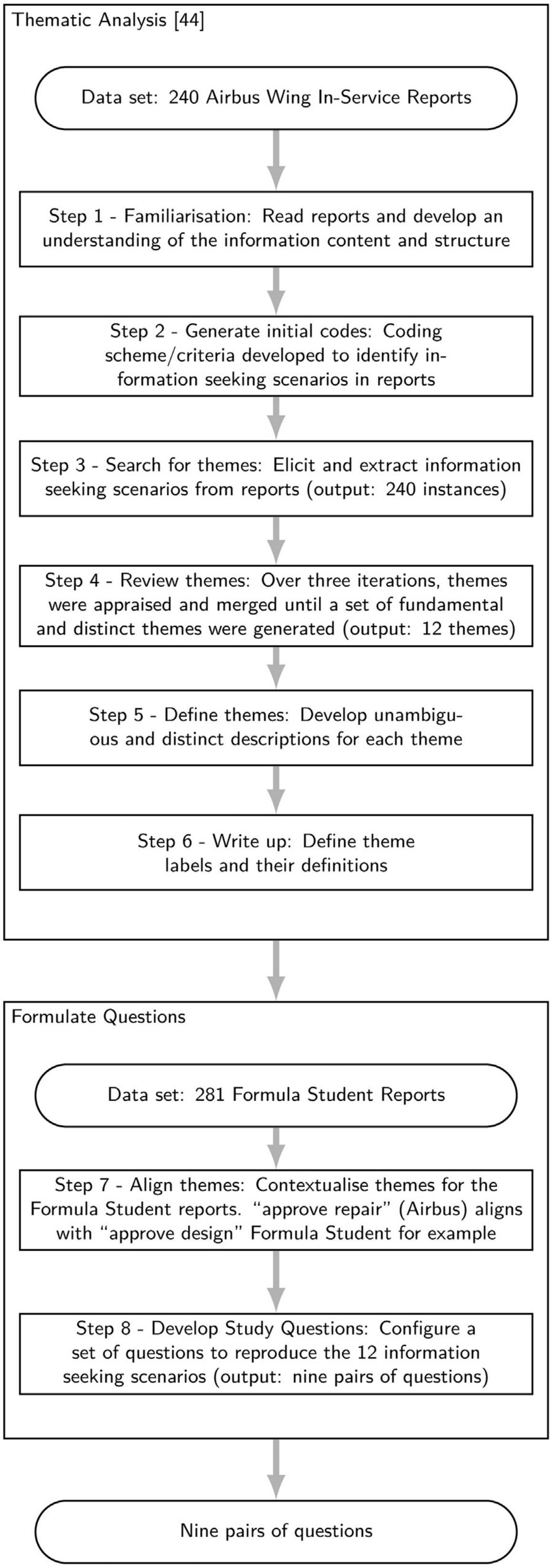


Fig. 6. Methodology diagram for capturing real-world engineering information seeking scenarios and transferring them to relevant questions.

Once themes were formally identified, these were then aligned with the corpus used for the A-B test (the Formula Student reports) and nine pairs of study questions were formulated. Each pair of study questions required the study participants to perform a discovered scenario. Study questions were formulated in pairs such that randomly, one of the pair would be asked on the text-based interface and the second of the pair would be asked on the model-based interface. Fig. 6 shows a methodology diagram for the discovery of engineering scenarios using a thematic analysis and the formulation of the nine pairs of study questions.

4.2. Information seeking scenarios and study questions

The engineering information seeking scenario(s) from each report were identified and extracted and are summarised in Table 1 (ID 1–12). In addition to analysing reports, the information seeking scenarios 13, 14, and 15 (Table 1) were derived from a semi-structured interviews held with the Wing In-Service team over the length of the study. These three study questions form knowledge discovery activities that are performed internally within the team, e.g. understanding the most frequent repair locations over a wing (13)/repair types (14) allows for a data driven resource allocation. While being able to apply repair knowledge contained within a seemingly unconnected past case (15), reduces turn-around given the repairs can be re-used rather than re-designed.

These 15 information seeking scenarios are then representative of the real-world activities performed by engineers. Table 2 then maps these scenarios to a list of 9 study questions (SQ) relating to the Formula Student use-case, with the questions being written by the authors such that each question required the participant to perform one of the information seeking scenarios. It is this list of questions that forms the basis of the study that members of Formula Student teams were asked to complete. Questions are in pairs (*a* and *b*) allowing each question to be asked on either interface. Questions number SQ4 and SQ9 contain three versions (*a*, *b*, and *c*), in both cases question *c* represents the version used in the first study with the UWE (University of the West of England) participants, the questions were replaced with the *b* version as participants appeared to be struggling to find the required information within reports. However, post study analysis showed no significant difference between the UWE and other participants and so the results for all studies were combined.

Table 3
A breakdown of the number of participants from each Formula Student team.

Organisation	Number
UWE	14
Bath	6
Bristol	19
Imperial	4

4.3. A-B study design

This section now outlines the methodology used to compare the model-based and text-based interfaces, starting with the structure of the study.

4.3.1. Study structure

In terms of the structure of the study, participants were first given a 15–20 min introduction to the study and the user interfaces, this included an overview of all the measures being captured, the purpose of the study, and a demonstration of both user interfaces. They were then given access to the system and 15 min to familiarise themselves with the operation of both interfaces. An hour and a half was then provided to answer the 18 questions. The order that the questions appeared was randomised for each participant and the interfaces were alternated such that for every pair of questions, one question would be randomly answered on each interface. The questionnaire was given to participants at the beginning of the study, participants were asked to complete the first section (demographics) at the beginning of the session, and the second section (IBM Computer System Usability Questionnaire (CSUQ) [45]) at the end of the session. See Fig. 7 for an overall structure.

4.3.2. Participants and locations

Formula Student teams from the University of Bristol, University of Bath, University of West England and Imperial College London participated in the study over four separate days. The size of the groups ranged from Imperial College London with four participants to the University of Bristol with 19 participants (see Table 3). Participants had engineering experience ranging for nought to five plus years and also performed a range of roles within their team, ranging from first year undergraduate CAD engineers to final year Masters level team leaders. A range of disciplines were also cov-

Table 2
A list of study questions (SQ) generated from engineering information seeking scenarios.

Question number	Question	Information seeking scenario
1.a	Can you find the document '2018 Supplementary Rules' by the Institution of Mechanical Engineers?	1
1.b	Can you find the textbook called 'Advanced Brake Technology' by Bert Breuer and Uwe Dausend?	1
2.a	Do you think that past teams have completed sufficient research into tyres such that suitable tyres could be specified for the current car without additional research?	2, 8
2.b	Do you think that past teams have completed enough research into impact attenuators that a past year's design could be re-used this year?	2, 8
3.a	Name the area(s) of the car that have received the most computational fluid dynamics analysis.	13
3.b	Name the area(s) of the car that have received the most finite element analysis.	13
4.a	Name a past supplier of sprocket carriers.	5
4.b	Name a past supplier of electric motors.	5
4.c	Name a past supplier of brake pads.	5
5.a	Has anyone explored the use of additive manufacturing for the tripod housing?	11, 4
5.b	Has anyone explored the use of additive manufacturing for the upright manufacture?	11, 4
6.a	Find a front wing general assembly drawing. Did the author include their name and if so, who created the drawing?	6, 9, 3
6.b	Find the main hoop technical drawing. Did the author include their name and if so, who created the drawing?	6, 9, 3
7.a	Find a report on active aerodynamics. What is the file called?	10, 12
7.b	Find a report on the use of analysis data to improve performance. What is the file called?	10, 12
8.a	What area(s) of the car did [redacted] work on?	14
8.b	What area(s) of the car did [redacted] work on?	14
9.a	Who would you contact for advice about carbon fibre wheel rims?	15, 7
9.b	Who would you contact for advice about front inboard suspension?	15, 7
9.c	Who would you contact for advice about rear outboard suspension?	15, 7

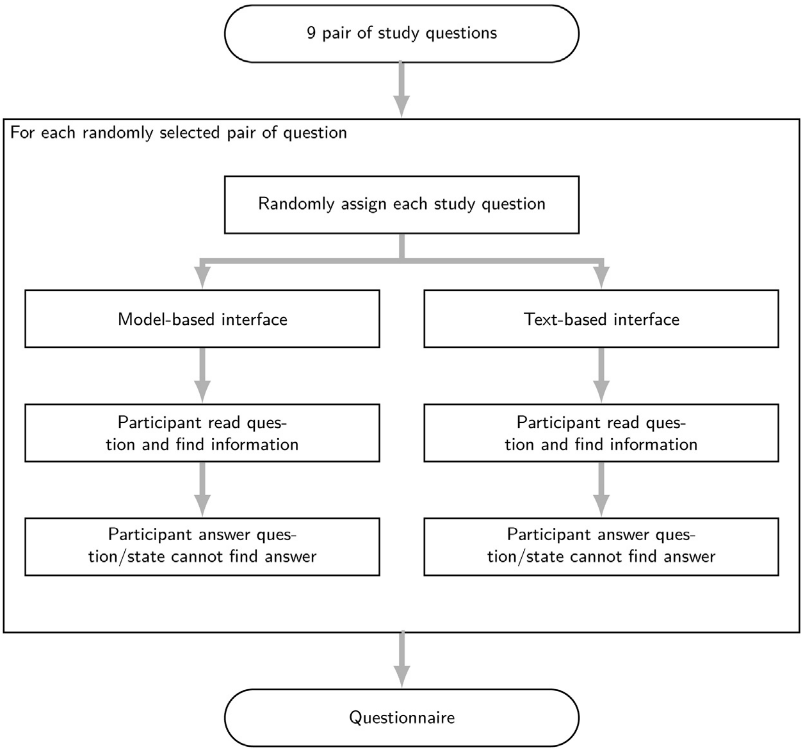


Fig. 7. Methodology diagram for the A-B study comparing a model-based interface to a text-based interface.

ered, ranging from aerospace engineers to electrical, mechanical and automotive engineers. These range of disciplines is comparable with those performed at the Airbus Wing In-Service team that were used to capture the information seeking scenarios used to generate the study questions.

Studies were held in general computer rooms at each teams' respective institutions. The computers used either Microsoft Windows 7 or Windows 10 and students were instructed to use the Google Chrome Web-browser to access the study website.

4.3.3. Experimental variables and performance measures

A model-based approach to document search is a research field that touches on a number of others, largely though, it is concerned with human-computer interaction, and information retrieval. In terms of evaluation in these fields, there is a disparity between the more qualitative measures used in human-computer interaction (e.g. thinking aloud), and the quantitative measures of information retrieval (e.g. f1-score). Fortunately, Catarci et al. [12] has presented an overview of information retrieval from the human-computer interaction perspective and it is the findings of their work that is used as the basis of the evaluation methods applied here. In particular and in line with Catarci et al. this paper adapts/uses: *total time*, *activities performed*, *success rate*, *number of reports accessed*, and *user feedback* (comments). When combined, these measures provide a general overview as to what participants are doing when engaging with both text-based and model-based interfaces. While these measures capture participant behaviour, they do not measure the effects of the system itself and the quality of the user interface, which can influence the former. Consequentially, measures of system usability and interface quality [45] are also captured,

Table 4 lists the seven measures in more detail, including their description, the means of capture, and the detail of how the measures are used for evaluation. The first being the *total time* to complete each study question captured in the system logs. This allows for a direct comparison between the two user interfaces with a shortest time being preferable. Traditional searching is split into two activities: time spent searching (formulating queries) and time spent browsing (scrolling through and evaluating) results. The model-based user interface adds an additional *activity*: navigating the model (moving within the three-dimensional space). Analysing the time spent searching and browsing should then provide some insight into how the model-based interface changes the manner in which participants engage with searching for information. Success rate measures i.e. whether participants were able to find the required information, and the number of *reports accessed* are taken as a measure of effort involved in the search – with a fewer number of reports being deemed a lower effort and so preferred over a higher number of reports. Finally, the questionnaire captures user feedback (comments) and their opinions on both the usability of the system and the interface quality. These allowed for qualitative insights into the participants' preferences for the model-based interface over the text-based interface. A thematic analysis [44] of feedback comments was performed to elicit common themes, such as whether participants preferred one interface over the other. The system usability and interface quality were explored using the IBM Computer System Usability Questionnaire (CSUQ) [45] which employs a Likert scale (0 to 7 with an n/a option) and provides insight into whether elements of the system implementation had any effect on the results, i.e. the system crashing.

Combining each of these measures can give a detailed picture of the impact of a model-based approach on information retrieval when compared to a more traditional text-based user interface. This is however all dependent on controlling the independent variables. These are listed in Table 5 along with the steps taken to mitigate their effect. The randomisation of the study question order and the interface was used to mitigate the effect of learning, and any unintentional bias in the study questions themselves. Maintaining a single back-end limited the impact of technology and indexing techniques as feasibly as possible, as did ensuring the participants used the Chrome web browser on a Windows 7 or Windows 10

Table 4
The list of measures presented from the A-B study.

Measure	Description	Capture method	Evaluation method
Total time (to complete each question)	The task level measure of total time to complete a question for both the model-based and text-based interface.	Using system interaction logs and for each question, the time taken was calculated between the first mouse-move event and the final mouse-over "End Button" event.	Outliers beyond two standard deviations are removed. Shapiro-Wilks test used to determine skewness of both the model-based and text-based results and these results then determined the significance test method – a Paired T-Test where both set of results are normally distributed and a Wilcoxon Test when they are not normally distributed.
Comparison of *activity* (*searching* and *browsing*)	For both interfaces, this is a breakdown of the percentage of time spent on navigation, searching and browsing activities during each task.	Using system logs, user interactions with the system were classified into navigation, searching, or browsing. With the time calculated being the difference between the start and end time of each activity.	A direct comparison of percentage of time spent on each activity across all participants. Can only be directly comparable when there is no significant difference between total time. Time spent performing activities relating to the task or those that could not be classified (participant moves the mouse off-screen) were ignored.
Answers retrieved (success rate)	Whether the participant could find an answer or not. No evaluation was made on the validity of the answers themselves, the rationale being that the participants are the domain experts and as such could judge themselves if an appropriate answer could be found.	The system captured user answers to questions. Participants were asked to provide an answer or state whether they could not find an answer. If an answer was provided, it was deemed a successful search i.e. there was no measure of the validity of the answers, just whether the participant felt they were able answer the question.	A direct comparison of percentage answer found/not found between each interface and across all participants.
Number of *reports accessed*	A measure of effort required to complete the task and the effectiveness of the search engines/ranking, i.e., the more reports accessed, the more effort required and the less effective the search engine/ranking.	From the system logs, an average number of reports accessed for each interface across all tasks.	Direct comparison of the average number of reports. The lower the number accessed, a lower number indicates a lower effort and therefore is more desirable.
Thematic analysis of feedback	A reflection on the participants opinions on the aspect of the interfaces/study that are relevant to the task/results presented.	IBM Computer Usability Satisfaction Questionnaire (CUSQ) questionnaire.	Key terms relating to the question/answer were used to pair questions to user comments '*brake pads*' for example.
System usability	The participant opinions about using the system.	IBM Computer Usability Satisfaction Questionnaire (CUSQ) questionnaire.	Summation of responses to questions 1-8 as recommended within the IBM guidelines for the questionnaire [45].
Interface quality	The participant opinions about using the quality.	IBM Computer Usability Satisfaction Questionnaire (CUSQ) questionnaire.	Summation of responses to questions 9-12 as recommended within the IBM guidelines for the questionnaire. [45]

Table 5
The list of independent variables and their description.

Independent variable	Description
Effect of learning	A random question order was used such that participants answered questions in a different random order, and so, if there was an element of learning during the study, its effect would be minimised.
Same search index used across both interfaces	Both interfaces use the same search index, effectively meaning that is the same "query" were used in both interfaces, the same results would be returned.
Presentation of results	Both interfaces use a side-ways scroll and an image of the front cover as a preview. Accessing report is done via clicking on the image, hence, the presentation of results is consistent across both interfaces and any effect in how results are presented is also consistent across interfaces.
Bias in the tasks	Tasks presented in a random order and random interface assignment to each task (a or b) and as such any effect from bias in the tasks should be minimised across the tasks.
Effect of browser/operating system	Participants were instructed to use the Chrome Web browser and Window 7 or 10 used throughout. There were no measures differences between performance on Windows 7 or 10.
Other: bug fixing/user interface changes between groups, network performance.	Each group given a demonstration of both interfaces, training and time for familiarisation in using both interfaces. In addition to this, when analysing results, outliers beyond two standard deviation removed and averages taken across all groups. Minimising and/or eliminating the impact of resultant effects.

operating system. The final steps are a catch all for other variables, such as bug fixes between studies for example. These include providing time for training and familiarisation as part of the study and in how results were analysed: outliers beyond two standard deviations were removed, results are averaged across all participants, a Shapiro-Wilk test was used to determine whether a Paired T-Test or Wilcoxon test was used to calculate any differences between the two user interfaces, and a probability-value of 0.05% was used to determine the significance of any difference. The purpose of all this was to ensure that the observed differences could be attributed to the model-based user interface.

5. Results

This section presents the results with respect to all questions, demographics, user preferences, and usability and interface quality.

5.1. Effects on all measures across all study questions

Table 6 shows the four measures of *total time*, *answers retrieved*, *reports accessed* and *activity (searching/browsing)* against each of the study questions (Table 2) and the corresponding activity ID (Table 1). These are followed by whether there is an increase (↑), decrease (↓), no difference (–) in the model-based interface when compared to the text-based interface, or whether the measures are not comparable (×). Positive effects are coloured green and negative effects coloured red. These results show how, for the *total time*,

Table 6
A comparison the model-based interface against text-based interface mean measures across study questions.

Study question	Activity ID	*Total time (S)*	*Answer retrieved (%)*	*Reports accessed (number of)*	*Activity: searching (% time)*	*Activity: browsing (% time)*
1	1	20.7 ↑	30.2 ↓	6 ↑	×	×
2	2, 8	–	17.5 ↓	6 ↓	22.3 ↓	–
3	13	–	23.8 ↓	2 ↓	16.1 ↓	–
4	5	–	–	2 ↓	–	12.2 ↓
5	11, 4	–	25.9 ↓	8 ↑	10.1 ↓	12.3 ↓
6	6, 9, 3	38.8 ↓	39.3 ↑	14 ↓	×	×
7	10, 12	22.9 ↓	15.3 ↓	–	×	×
8	14	–	8.3 ↓	6 ↓	19.5 ↓	–
9	15, 7	6.5 ↑	4.0 ↓	7 ↑	×	×

↑, Increase compared to text-based interface; ↓, Decrease compared to text-based interface; –, No difference; ×, Not comparable; Red, Negative effect; Green, Positive effect.

the model-based interface was on two occasions quicker than the text-based interface, on two occasions slower and there was no significant difference for the remaining five study questions. For the *answers retrieved* measure, using the model-based interface, participants were less likely to find an answer in seven of the nine study questions, more likely in one of the nine study questions and with no difference in one of the nine study questions. The *reports accessed* results show that the participants accessed more reports on three of the nine study questions, fewer reports on five of the nine study questions with no difference for one of the nine study questions. In terms of *activity*, the results are spilt into time spent searching and browsing. There was no time spent navigating using the text-based interface and so no comparison can be made, results should be interpreted with this additional *activity* in mind however. For time spent searching, for four of the five study questions, there was less time spent searching using the model-based interface compared to the text-based interface. For time spent browsing, there was a reduction in browsing time in two of the five study questions. At no point was there an increase in either searching or browsing using the model-based interface compared to the text-based interface.

Examining these in terms of the information seeking scenarios: there is an increase in time for the *analyse extend of damage*, *report manufacture issue*, and *identify new knowledge from a seemingly unconnected past case* activities when comparing the model-based interface against the text-based interface. There is also a decrease in time for the *provide technical drawing*, *instruct on inspection methods*, *provide repair instructions*, *provide aerodynamics analysis*, and *search for similar incident* activities when comparing the model-based interface to the text-based interface. In terms of *total time*, there was no significant difference for the remaining activities. To summarise, there is a decrease in time for five of the 15 activities, and increase in three of the 15 activities and no difference in seven of the 15 activities when comparing the model-based interface to the text-based interface.

When examining the success rate of the participants finding answers to study questions, participants were less likely to find an answer using the model-based interface in all but three activities. Participants were more likely to find an answer when performing the *provide information* and *approval for use of new material in repair* activities and there was no difference with the *order item* activity.

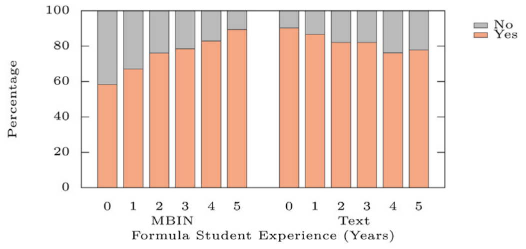
Using the model-based interface, participants accessed fewer reports for eight of the 15 activities and more reports for five of the 15 activities compared to the text-based interface. The number of *reports accessed* were the same for two of the activities.

Finally, in terms of the *activity*, participants spent less time searching for six of the 15 activities and the same time in one *activity*. Time spent browsing was reduced for three activities and the same for three activities. There was only one occasion where both searching and browsing times were lower. These are all when comparing the model-based interface to the text-based interface.

Through inspection of Table 1 and the top four activities with the highest frequency from the 240 reports analysed: these four activities (*provide repair instructions*, *evaluate propose repair*, *analyse extent of damage*, and *approve repair*) correspond to approximately 95% of all the activities classified. Combining these with the results in Table 6 it is shown that the *activity* with the highest frequency had a reduction in *total time*, an increase in the *answers retrieved* and a decrease in the number of *reports accessed*. The second and fourth most frequently performed information seeking scenario showed no difference in *total time*, and a reduction in the number of *answers retrieved* and *reports accessed*. The third highest shows an increase in time, a reduction in the *answers retrieved*, and an increase in the *reports accessed*.

5.2. *Demographics: FS experience and leadership*

Fig. 8a shows the participants' *success rate* in answering all study questions broken down by their experience in Formula Student from zero years to five years. The graph shows a linear correlation between experience in Formula Student, and the likelihood of the participant finding an answer using the model-based interface. At zero years, average participants are only able to find a result 60% of the time and this steadily rises to nearly 90% at five years. Equalling the maximum level achieved by participants using the text-based system. In contrast, the results for the text-based system start at

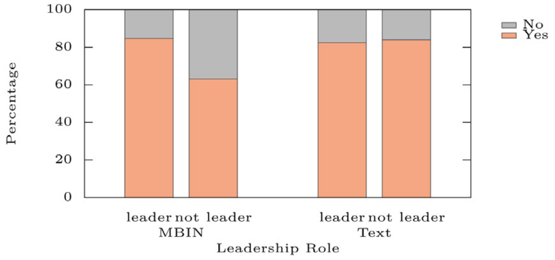


(a)

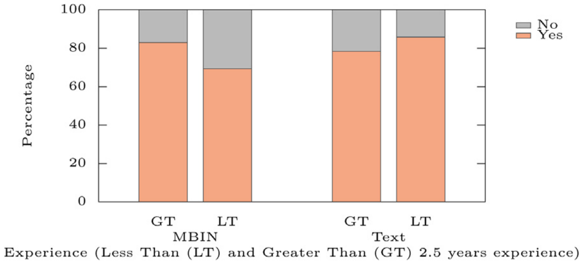
Measure	MBIN	Text
Slope	5.88	-2.70
R-squared	0.97	0.90
p-value	0.00	0.00
Standard Error	0.55	0.45

(b)

Fig. 8. Answer success rate by Formula Student experience and associated linear correlation statistics for both interfaces.



(a) Leadership



(b) Experience

Fig. 9. Answer success rate by participant leadership role (a) or experience (b) for both interfaces.

the maximum of nearly 90% before dropping to just below 80% for the most experienced participants.

The second finding relates to the study question answering *success rate* and whether the participant is in a leadership role or not. Fig. 9a shows the mean *success rate* broken down by whether the participant is in a leadership role, for both the model-based and text-based interfaces. The figure shows a *success rate* of over 80% for all those participants apart from those in a non-leadership role using the model-based interface where the *success rate* falls to approximately 60%. This aligns somewhat with the results shown in Fig. 8a, which suggests that the more experienced a participant is, the more likely they are too be in a leadership role. Fig. 9b shows the results for participants split by their years of Formula Student experience (above (GT) and below (LT) 2.5 years). Comparing Fig. 9a and b directly shows the difference between the effect of leadership against experience.

The most obvious difference between the two Figures is that those with less experience are more likely to find information with the model-based (Fig. 9b) interface than those who are not leaders (Fig. 9a). Given some participants are both leaders and have less experience, this indicates that both leadership and experience have an influence on the ability to find an answer using the model-based interface.

Table 7
A list of themes and their descriptions, derived from participant feedback comments.

Theme	Description	Freq.
preference: model-based interface	Statement of preference for the model-based interface	30
preference: *both at once*	Statement of preference for access to both interfaces	14
Technical problems	System or technical problems, the system crashing for example	11
More time needed	More time needed for familiarisation with model-based interface	6
preference: text interface	Statement of preference for the text-based interface	5
search problems	Search engine not performing as expected	5
text more familiar	Text-based interface more familiar than model-based interface	4

5.3. User feedback

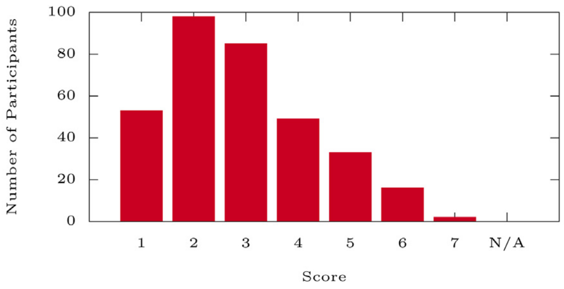
The thematic analysis of questionnaire feedback comments revealed a number of themes: *technical problems*, *search problems*, *text more familiar*, *need more time*, *preference* and *both at once*. Table 7 shows the list of themes identified and their descriptions.

Firstly, one cannot ignore the fact that some users had technical problems (ID 1 in Table 7). The system re-set if the user pressed the back-button or refreshed the page and most if not all of the reported 'crashes' were due to the participant accidentally performing one of these actions. Other issues, such as text-boxes not clearing or the search boxes not responding to numbers, were consistent between the two interfaces and as such should not have had an effect on the results presented.

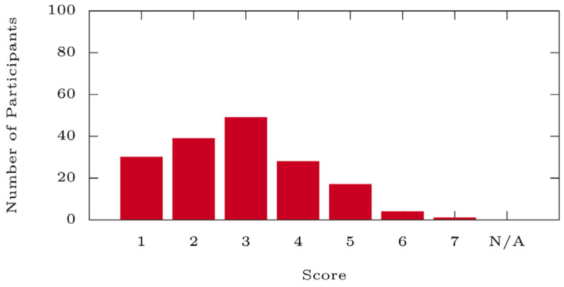
Secondly, and categorised as *search problems*, the ranking method employed, the TD-IDF weighting, was not always the most useful measure to rank by (speaking to the wider difficulties in developing successful enterprise-type search engines [8,10]). The ranking method was the same for both interfaces and as such this was mitigated against in the design.

The *text more familiar* category shows some participants noted how the text-based interface was more familiar (from life outside the study) and as such may have had an advantage, this was reflected in comments that stated the participant felt they would improve with more time with the system (the *need more time* category). The comments seem to suggest that the 15–20 min provided at the beginning of the study was adequate for some participants but not for all participants. It is not possible to say how much of an effect that this may have had on the results presented. However, the finding that those more experienced in Formula Student are more likely to successfully answer questions does suggest that a longer period of familiarisation would improve results and so repeating the study after providing the system to participants over periods of months could mitigate this.

In terms of the *preference* between the two interfaces a far greater number of positive comments in favour of the model-based interface (30) compared to positive comments for the text-based interface (5). Participants both understood the potential benefits of the model-based interface in spite of any perceived short-comings (e.g. system crashing, poor ranking) in the implementation or search engine. A number of comments note how the system was intuitive to use, with some noting how the model-based interface made searching for information easier. The final category and relating to the *preference*, *both at once*, show 14 participants would have preferred to have access to both interfaces at the same time and be free to switch between the two.



(a) An accumulation of the scores from CSUQ question 1 to 8 that form the system usability proportion of the questionnaire.



(b) An accumulation of the scores from CSUQ question 9 to 12 that form the system interface quality proportion of the questionnaire.

Fig. 10. The accumulated responses to the CSUQ Questionnaire.

5.4. System usability and user interface quality

Fig. 10a shows the accumulated responses from CSUQ questions 1 to 8 that are used to evaluate the system usage. The scores range from a positive response (1) to a negative response (7), with a not applicable (n/a) option. These results show a clear positive response to using the model-based interface, with there being a peak at the score of 2.

Fig. 10b shows the accumulated response from CSUQ questions 9 to 12 that are used to evaluate the quality of the interface. Here, there is a peak at the score of 3, however, most scores still sit on the positive side of the scale, i.e. a score less than the half way point on the scale (a score of 4). Combined, the two Figures show a positive response to the model-based interface in spite some perceived issues with the quality of the system.

6. Discussion

Overall the results presented in this paper are mixed. Exploring the key measure of time to complete each study question (see Table 6) across the nine pairs of study questions revealed four showed significant differences: two in favour of the model-based interface and two in favour of the text-based interface. For the remaining five study questions there was no significant difference. This is an interesting finding given that the model-based interface adds an additional and complex step to the search process (navigating the three-dimensional model) and yet in most cases, this does not slow the search process. Where the participant *activity* can be broken down into search, navigation and browsing, and the results allow a direct comparison of time spent performing each study question, they show the time spent navigating reduces the time spent formulating search queries and occasionally some time spent browsing.

The two largest differences in times, study questions SQ1 (approximately 20 s in favour of the text-based interface) and study question SQ6 (approximately 35 s in favour of the model-based interface), both had additional factors influencing the search. In study question SQ1, one document is related to a specific component and the other is a more general document relating to a Formula Student racing car system. This highlighted how some users struggled with the concept of how that second document is associated with the model and this could have had a negative impact on the model-based times which would not have been present in the text-based times. With study question SQ6, the text-based method was not capable of indexing drawings whereas the model-based interface was. The number of *reports accessed* via the text-based interface were also far higher with this study question than any other. The 35-s difference is then clearly down to the fact that users could not find the relevant drawing using the text-based interface. The fact that the model-based interface allows for the indexing and finding of drawings has been highlighted as an affordance of the model-based interface.

The participants' ability to retrieve information was lower with the model-based interface in seven of the nine study questions, roughly the same in one study question and higher in the aforementioned drawing study question. The results do however show that factors of experience and role impacts the results with both interfaces performing roughly equally at five years of experience and for holding a leadership role, with an interesting element of this being a trend between participant experience and difficulty in finding answers. The reason for this is unclear with no explanation being found within the results captured, however, literature on how experts perform internet searches presented by Tabatabai et al. [46] reported similar results in that experts did not perform as well as expected, and those deem as having an intermediate expertise performed better than expected. Tabatabai et al. speculated that this could be due to the work presented by [47] on how, as people become experts, their knowledge becomes more specialised within a specific domain, where as those with less experience have a more general knowledge about that domain, and that the questions ask were better suited to those with a more general rather than specific domain expertise. This manner of gaining knowledge mirrors the teaching approaches at many Universities, as students begin with a general overview of the field before choosing to focus in a particular areas. The questions asked in the work presented here (Table 2) are also general in nature. If Tabatabai et al.'s speculation is true, then it would appear that the model-based interface overcomes the problem, however, without further research this is still speculation.

6.1. Industrial implications

As previously stated, the results revealed that experience in the Formula Student project and whether the participant is in a leadership role impacts performance. This is likely due to the participants' familiarity with the model they see on-screen and the understanding of the wider project – where components are located within the car and the arrangement of components within systems and subsystems. Returning to the Airbus use-case, the In-Service department design repairs for in-service products and as such, the engineers working in those departments are familiar with the product and hence, should perform better than the students used in this study. It can be said then that the results show that the model-based interface is more suitable to products after the design phase of the product life-cycle, where engineers are more familiar with the product structure.

When combining the results with the list of Airbus Wing In-Service activities and frequency (Table 1) the picture is mixed. If one considers an improvement in information access and knowledge discovery as a reduction in *total time*, an increase in the number of *answers retrieved* and a reduction in the number of *reports accessed*, then the results show an improvement for the most frequent question (*provide repair instruction*). However, the second and fourth most frequent activities show no difference in *total time*, a reduction in *answers retrieved* and a reduction in the number of *reports accessed* and the third highest *activity* shows an increase in time, a reduction in *answers retrieved* and an increase in the number of *reports accessed*. So on this analysis, the picture is again mixed.

There were a number of comments that describe the model-based interface as intuitive, simple and easy to use and that it aided and supported the finding of information. This was reflected in the responses to the scores submitted in response to the system usage. Alongside this, and on a more cautious note, in terms of a day-to-day implementation, participants also commented that they would prefer both systems side-by-side. While participants enjoy using the model-based interface, there is a learning curve associated with both familiarisation with the project as well as the model-based interface. Providing both forms on interface mitigates this and the expectations would be that over time, users would naturally migrate to the model-based interface.

7. Conclusion

Work in the area of improving Intranet/enterprise search is on-going however, one area of the problem space that has not received much academic consideration is the form of the interface and opportunities to create interfaces that capitalise on the visual and functional nature of how engineers think and the engineering process. This paper addresses this gap by building on model-based approaches to engineering and developing and evaluating a model-based information navigation system.

In an A-B test with a traditional text-based search engine, and using study questions derived from real-world information-seeking scenarios based on the activities of a world leading aircraft manufacturer, the results presented in this paper suggest that in answer to whether a model-based interface improves engineering information retrieval:

- there is no significant difference in time to complete a search in spite of the addition of a new stage in the search process;
- the system structure of the model-based interface allows for non-text based documents to be indexed, making up for the inherent limitations in traditional text-based search;
- participants unfamiliar to the product (structure) will be less likely to find answers than those who are familiar with the product;
- participants who are managers or hold more senior technical roles are more likely to find information that those who are not leaders; and,
- participants enjoy using the model-based interface and find it intuitive, easy and simple to use.

However, the concept would benefit from wider and longer term study to overcome the fact that most users are highly familiar with text-based search engines and any alternative requires a change in mental models and practice. Based on the results presented here, the main recommendation of this work is that, in practice, both a traditional text-based and a model-based system should be provided side-by-side; allowing the user to determine which they prefer for any given information seeking scenario and thereby leveraging the affordances of each.

Author contributions

David Jones: Conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing – original draft, writing – review & editing, visualisation, project administration

Chris Snider: Conceptualization, methodology, writing – review & editing, project administration, supervision

Jason Matthews: Resources

Jason Yon: Resources

Kevin Robinson: Resources

Ben Hicks: Conceptualization, methodology, writing – review & editing, project administration, funding acquisition, supervision

Conflict of interest

The authors declare that there is no conflict of interest.

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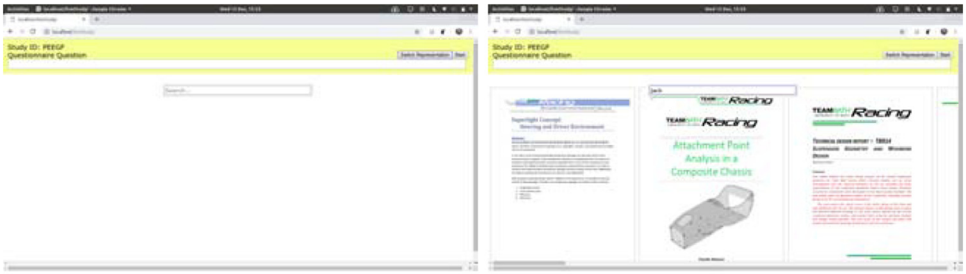
Appendix A. User journeys

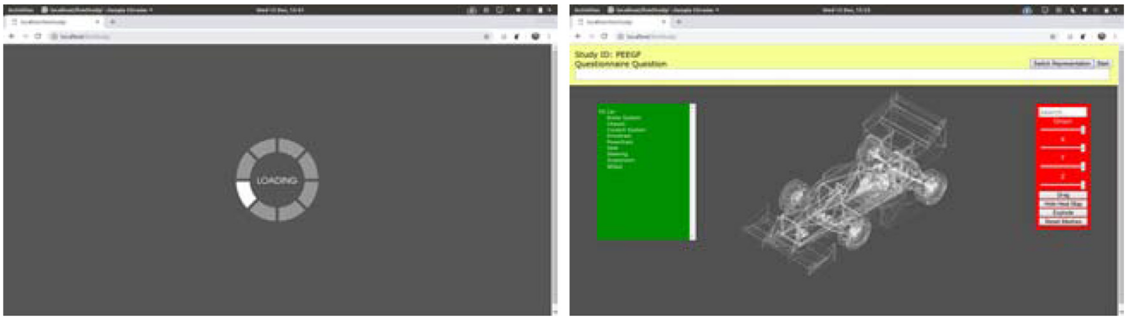
A.1 Text-based search engine



(a) Initial view of the text-based search engine

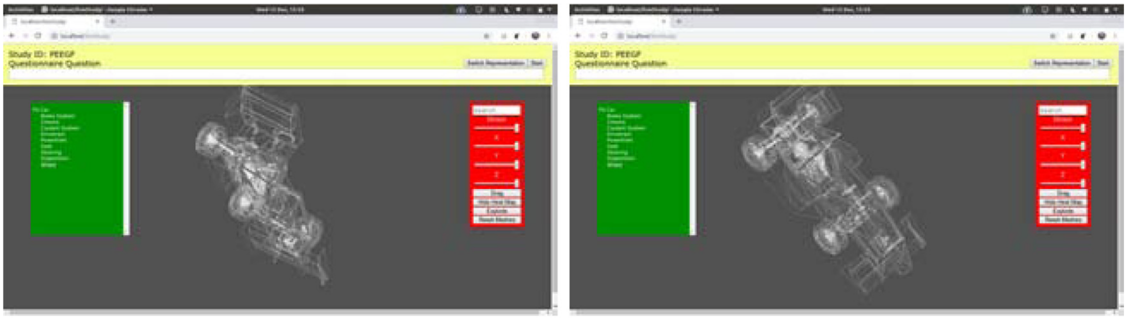
(b) The results panel from the text-based search engine. Clicking on a report front page opens up the report in another browser tab.

A.2 Model-based system



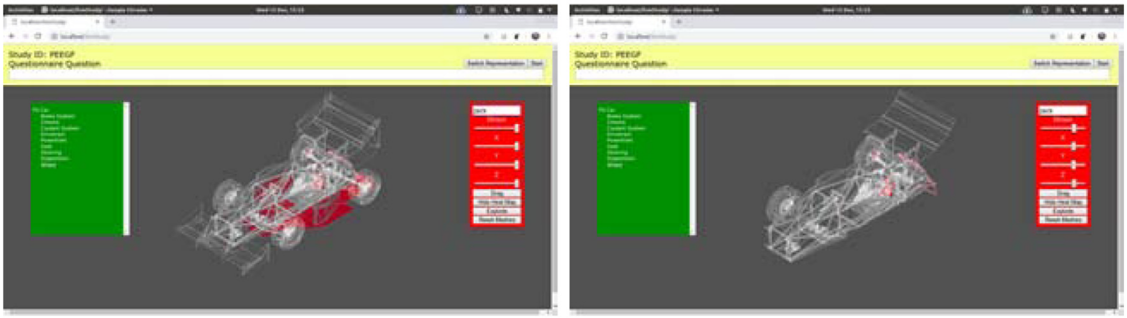
(c) Loading Screen

(d) Initial view of the model-based system



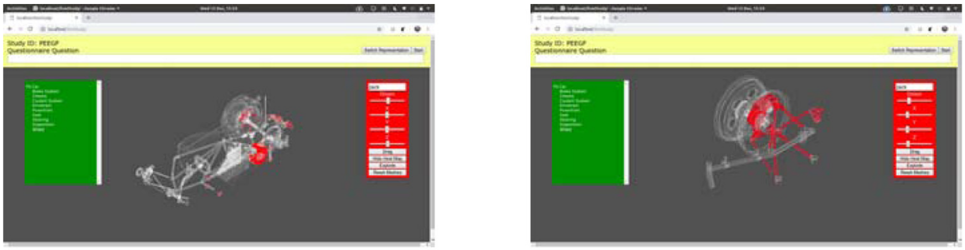
(e) Navigating the virtual environment by ‘grabbing’ and ‘rotating’ using the mouse.

(f) Further navigation of the virtual environment.

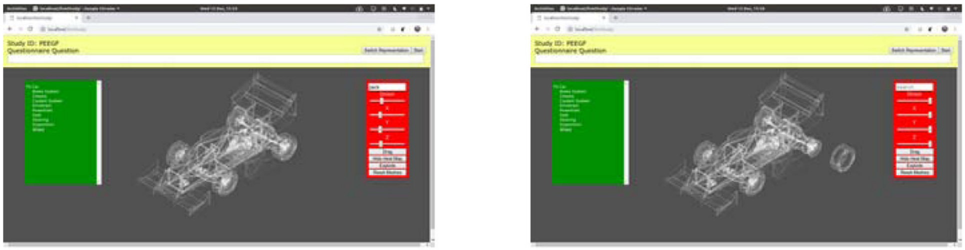


(g) Using the heat-map search facility within the red panel on the right.

(h) Onion peeling through the car using the controls in the red panel on the right.

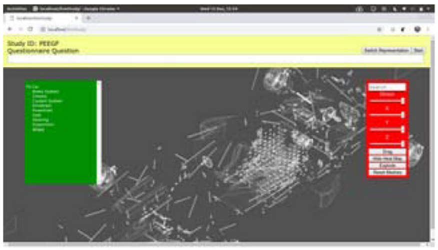


(i) Further onion peeling. (j) Further onion peeling.

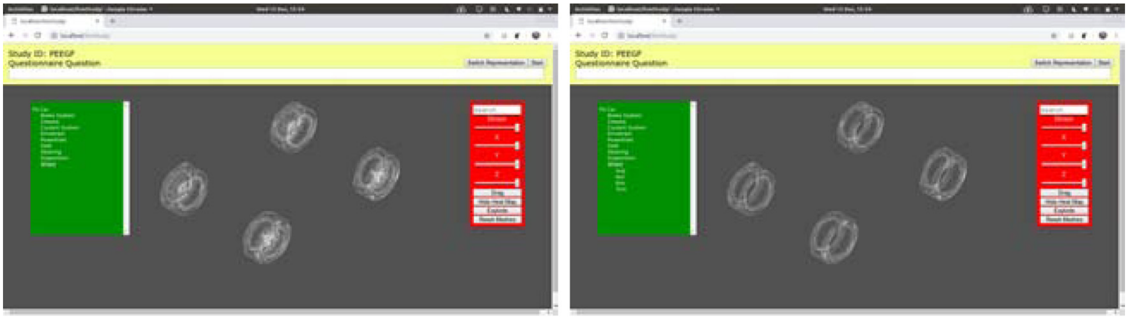


(k) Re-set mesh in the red-panel on the right re-sets the virtual environment.

(l) Using the manual manipulation of components, enabled in the red panel on the right.

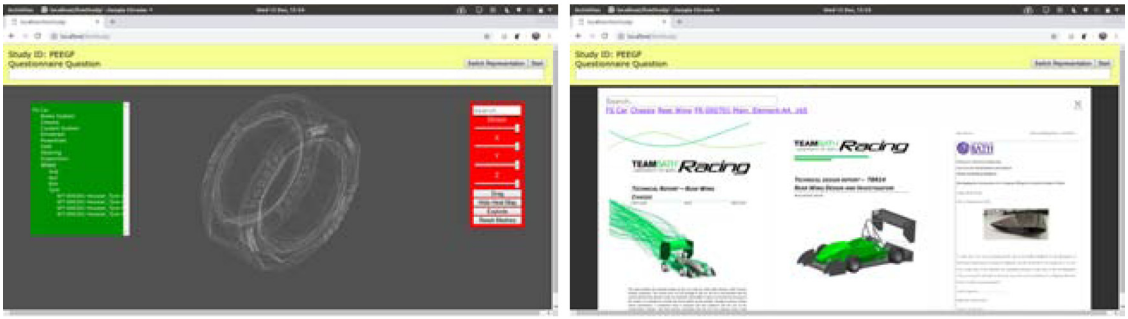


(m) The exploded view, enabled by clicking the 'Exploded View' button in the red panel on the right.



(n) Selecting systems/subsystems using the green panel on the left. Here the wheels are selected.

(o) Further selection of systems/subsystems using the green panel on the left. Here the tyres are selected.



(p) Further selection of a system/subsystem using the green panel on the left. Here an individual tyre is selected.

(q) The results panel from the model-based system showing results for a particular component.

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