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CHARACTERISING THE INFORMATION REQUESTS OF ENGINEERING DESIGNERS

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1. Introduction

Current manufacturing organisations need to improve the quality of their products and the efficiency of their processes in order to operate in a global market economy that continually demands shorter product lifecycles and reduced costs. It is known that designers can spend up to a quarter of their time in information acquisition. Ensuring that designers find satisfactory answers to their information requests in the shortest time is therefore a key issue. In order to improve the support given to designers in this area, it is important to have a deeper understanding of information requests and searches. A literature review of current empirical studies on information requests and searches found that little research has been undertaken on this topic. Hence, a research project was carried out in collaboration with the aerospace group of a major power systems company, with the aims of characterising: (1) the requests formed when designing that make engineering designers search through external sources; and (2) the searches undertaken to find answers to those requests. In this project, information requests and searches were studied using an ethnographic participation, a diary study and observations with shadowing. This paper presents the research undertaken to characterise information requests based on their *objective*, *subject* and *response process*. An information request can be considered as a speech act or conscious thought expressing a need related to the design task in hand. In previous design research, the information requests of designers were also referred to as questions, queries or requirements.

2. Literature

2.1 Current studies on information requests

At an early stage of this project, four empirical studies into the requests formed when designing were reviewed with the aim of analysing their methodological approaches and contributions [Kuffner, 1991; Gruber, 1992; Baya, 1996; Eris, 2002]. The review of the methodological approaches found that the research was always conducted in laboratory environments and the data was collected using verbal protocol analysis. Studying information requests in such environments is a limitation because they do not take into account the effects of social and situational factors on the design process nor the complexity of designing technical products in industry.

The review of the classifications of information requests found that in only Eris's study was a hierarchical structure proposed, i.e. the classifications for the other three were flat. The classifications were analysed in order to identify key characteristics of information requests that could be used as a basis for a new classification. The analysis indicated that a new study on information requests should give more rigorous consideration to the activities of problem solving and reasoning. Overall, current classifications of information requests were incomplete and the need for a deeper understanding of information requests was identified.

2.2 Problem solving

The engineering design process can be viewed as a human problem solving activity. Models of problem solving have been proposed by Ullman and Gero [Ullman, 1988; Gero, 1990]. The sequences of activities proposed in these models included the pattern generation-evaluation. However, evaluation is regarded differently by the two researchers. Ullman considers evaluation to include both the analysis of a solution and the comparison of its behaviour predictions against the requirements and other criteria. Differently, Gero clearly distinguishes analysis from evaluation. Analysis consists in deriving behaviour predictions from the generated solution. In this research project, the activities undertaken in problem solving follow the pattern *generation-analysis-evaluation*.

2.3 Reasoning

Engineering design involves reasoning from a set of needs and requirements to generate the form of a product. *Reasoning* can be defined as the process of making an inference from an initial proposition (IP) to a final proposition (FP). In design, the IP and the FP are descriptions of a product in terms of behaviour and form as well as additional drivers in the design process, e.g. manufacturing, cost, etc. Consider for example the following request: *How can we flood the oil in the gearbox?* This request expresses the intent to move from an intended behaviour (IP: flooding/distributing oil) to a form (FP: physical concept to flood/distribute oil) by reasoning. In design research, models of the reasoning process have been proposed by March, Coyne and Roozenburg [March, 1984; Coyne, 1988; Roozenburg, 1993]. In these models, two main types of reasoning are distinguished: deduction and reduction. Deduction is logically valid reasoning and consists in inferring an effect (FP:q) from a cause (IP: p) by means of a rule (IP: $p \rightarrow q$). In design, this type of reasoning supports, for example, analysis. The move from form to predicted behaviour is commonly undertaken in the simulation of a design concept. Simulation comprises the construction of a model and deduction based on that model. Reduction has three different forms: (1) induction; (2) abduction; and (3) innoduction. These are all forms of plausible, nondemonstrative reasoning that have important roles in problem solving in science and technology [Roozenburg, 1993]. Induction consists of inferring a general rule (FP: $p \rightarrow q$) from a set of particular rules (IP: $p1 \rightarrow q1$; $p2 \rightarrow q2$; …). This type of reasoning has an important role in the empirical sciences, as scientists aim to make general statements about the world in terms of laws and theories. In design, this type of reasoning appears to support, for example, evaluation. The move from predicted behaviour to intended behaviour is undertaken to match a prediction generated from a possible design with a specific requirement [March, 1984; Patel, 1997]. Abduction, also termed non-creative abduction, consists of inferring the cause of an effect (FP: p) to be explained, from a rule (IP: $p \rightarrow q$) and an effect (IP: q). In design, this type of reasoning supports, for example, generation to explain existing solutions. The move from intended behaviour to form is generally employed to revisit existing designs. Innoduction, also termed creative abduction, consists of inferring a new rule (FP: $p \rightarrow q$) and a new cause (FP: q) from an effect (IP: q). In design, this type of reasoning supports, for example, generation to construct new solutions. The move from intended behaviour to form is the key mode of reasoning to develop new designs.

Engineering design also entails undertaking more complex reasoning processes. Dialogue theory involves studying reasoning and decision making as they actually occur in the interactions between people. Walton and Krabbe, working in the tradition of argumentation theory and informal logic, developed a framework that classifies a range of dialogue types [Walton and Krabbe, 1995]. These dialogue types are useful when studying compound information requests that are responded to by making multiple inferences.

3. Research approach

The approach developed in this project for studying information requests and information searches consisted of integrating ethnographic participation with analytic empirical methods. Ethnography, a research technique from social sciences, does not sit easily alongside standard empirical design research methods, because of their contrasting philosophical bases in personal subjective experience and objective hypothetico-deductive methods respectively. However, in this project ethnographic participation was used as part of a preliminary research phase, in order to generate new insights into the nature of information requests. The research approach evolved using indications from the literature review, insights from the data gathered as the research progressed, and constraints imposed by carrying out research in industry.

The approach consisted of two main phases. During phase 1, two studies were undertaken: ethnographic participation; and diary study plus in-depth interviews. During phase 2, observations with shadowing were conducted. The two phases were separated by approximately twelve months. This enabled the results of the first phase to inform the second. Each of the studies was designed to develop an understanding of the nature of information requests. The employment of three different types of studies enabled the data to be triangulated and thus increase the objectivity of the overall results. All the studies were conducted in one of the design departments of the collaborating company. The design tasks studied were variant designs, i.e. the work usually involved incremental innovation to extend existing product solutions.

During the nine-week ethnographic participation, the researcher carried out design work under the supervision of an experienced designer. The participation led to a good understanding of design practice in the company and allowed a preliminary set of observations about information requests to be gathered. In addition, the participation helped shape the direction of the research project with respect to the definition of the aims and the selection of the subsequent data collection methods.

The five-week diary study provided an opportunity to capture in real time, the requests formed when designing, without the presence of the researcher. Twelve engineers agreed to self report their requests whenever they occurred. A diary study was selected because it facilitated: (1) the gathering of information about a large number of requests; (2) the collection of requests over an extended time period; and (3) the involvement of many individuals. In order to strengthen the investigative capability of the diary study, in-depth semi-structured interviews with audio-recording were undertaken at the end of each week. These interviews were intended to enrich the information space around a request. Overall, a total of 245 original requests were collected. Although the participation in the diary study was below expectations, the study provided enough data to conduct an exploratory analysis into the nature of requests.

The observations provided an opportunity to capture at first hand the requests formed when designing. Ten engineering designers were observed for seven hours each. Prior to the start of an observation, each participant was asked to follow his or her daily schedule and to think aloud to express any information request requiring an external search. The observations were followed by interviews. Overall, a total of 241 original requests was collected. The observations were found to be the method that provided the richest data and the greatest number of insights.

4. Development and use of the objective, subject and response process categories

The literature review and the studies undertaken in this project led to the identification of six characteristics of requests that were used to structure a new classification. The characteristics were: (1) objective; (2) subject; (3) response process; (4) response type; (5) direction of reasoning; and (6) behaviour type. A *category* including a number of descriptive *types* was generated for each characteristic. This paper presents the development and use of the first three categories and their types, i.e. objective, subject and response process. The remaining three categories are not presented here.

The *objective* of an information request describes the intent of the designer. Analysing current classifications of information requests and the two data sets, the researcher gained an understanding of how designers use information requests in the design process and developed an initial list of objectives. The first important finding was that some requests do not indicate an objective, whereas others indicate specific objectives, e.g. confirmation, comparison, generation, analysis and evaluation. Consider for example the difference between a request to obtain information, e.g. *What is the coefficient of thermal expansion of this material?* and a request to analyse a solution, e.g. *What could be the movements of this part?* Among the requests indicating an objective, it was found that some requests were formed to pursue low level objectives, e.g. confirmation and comparison, whereas others were formed to pursue high level objectives typical of problem solving, e.g. generation, analysis and evaluation. Low and high level objectives are conceptually distinct and operate at different levels of design thinking. Consider for example the difference between a request to compare operational parameters, e.g. *What is the temperature and pressure difference between the Antle and the Trent 500 in the seal position?* and a request to generate a dimension, e.g. *How much should the diameter of the shroud to the Trent 900 radial drive shaft be increased to scavenge oil adequately?* At this stage of the research, the list of objectives included information, confirmation, comparison, generation, analysis and evaluation. Further analysis of the two data sets showed that this list of objectives still did not permit the characterisation of some important differences in the nature of information requests. Two main issues emerged concerning the *generation* objective. The first main issue is discussed here with reference to design problems. In design, generation entails moving from an intended behaviour to a form. Designers were found forming information requests to move from intended behaviour to form, both to develop new solutions and to revisit existing solutions. Hence, in order to characterise this difference, two types of generation were identified and termed *constructive generation* and *explanatory generation* respectively. Consider for example the situation in which a designer working on a gearbox design forms a request to develop a new concept to flood oil, e.g. *How can we flood the oil in the Trent 900 gearbox?* Assume now that the same designer, before generating this new concept to flood oil, forms three further requests to revisit existing concepts to flood oil, e.g. *How did we flood the oil in the Trent 500 gearbox? How does oil flood in the Trent 700 gearbox?* and *How do we flood oil in other areas of the engine?* It is noteworthy that the first of these four requests is the only one that can lead to the construction of a new solution, the others having been formed to explain existing solutions. Among the last three requests, the first two ask what concepts were used in past projects to provide the intended behaviour, whereas the last one asks what concepts were used in other product areas. It is interesting that in the final request example the designer's reasoning moves away from the specific situation on which he is working to look for new product areas where that particular intended behaviour was satisfied.

The second main issue is related to the finding that designers form requests to generate solutions to different problem types, including design and diagnosis. Consider for example the situation in which a designer, working on the radial drive shaft bearings, forms a request to figure out the best position for the oil feed to the bearing cage, e.g. *Where can I bring the oil jet in to best feed the bearing cage?* Assume now that the same designer is approached by his supervisor and asked to carry out a diagnosis. Hence, the designer forms a request to identify the cause of a problem that emerged during engine development, e.g. *What caused the oil leak?* If the first request expresses the intent to move from an intended behaviour to a form, the second one expresses the intent to move from an undesired behaviour to a problem in the existing form. After the consideration of this issue, it was decided that the difference between these two types of generation would not be addressed by the *objective* category. Instead this difference would be addressed by the *direction of reasoning* and *behaviour type* categories, which are not presented in this paper. Table 1 presents the final list of objectives that were derived from the analysis.

Table 1. Objective category

TYPE	DESCRIPTIONS
Information	The request wants to obtain information but does not indicate an objective. Ex.: *What material does the Trent 800 use for this part?*
Confirmation	The request wants to establish the truth of a fact, the occurrence of an event or the existence of a state. Ex.: *Is the weldability of crown max-c and jethete as good as the material database suggests?*
Comparison	The request wants to establish similarities and/or differences. Ex.: *What are the differences in inspection requirements between a class 01 and class 02 forging?*

Constructive generation	The request wants to generate a solution: from the generation of creative conceptual solutions to that of detailed features of solutions. Ex.: *How can I retain the seal in place?*
Explanatory generation	The request wants to generate an explanation: from the generation of explanatory conceptual solutions to that of detailed features of solutions. Ex.: *How does oil scavenge from that side of the chamber?*
Analysis	The request wants to establish the consequences of a solution by carrying out simulation and calculation. Ex.: *What is the impact on stress of increasing the OD of the shroud?*
Evaluation	The request wants to establish: (i) if a solution is satisfactory or not and, in the affirmative case, the degree of merit by comparing its consequences with the requirements and other criteria; and (ii) the degree o merit of a number of solutions by relative comparison. Ex.: *Is the stress in the HPIP hub acceptable?*

The *subject* of an information request describes the major object of interest. Table 2 presents the list of subjects.

Table 2. Subject category

TYPE	DESCRIPTION
Product	The request refers to the artefact being designed and anything that contributes to defining it. Product requests includes: geometry definitions; standard geometry specifications; parts; standard parts; assemblies, material definitions; manufacturing definitions; product requirements; etc. Ex.: *How can I retain the seal in place?*
Process	The request refers to any process. Process requests include: manufacturing procedures, capacities, possibilities, speeds and capabilities; material performances and properties; technical reports and drawings; tools for design, analysis and management; process requirements; procedures for problem solving, analysis and management; etc. Ex.: *Where could I best start this task?*

The *response process* of an information request describes the cognitive process involved in finding an answer. Analysing the classification proposed by Eris, reasoning emerged as the process to answer information requests to solve problems [Eris, 2002]. Analysing the two data sets, it was found that a clear difference can be found between information requests that are responded to by making an inference from an IP to a FP and requests that are responded to by finding and returning information. In order to characterise this difference, two types of response process were identified and termed *reasoning* and *retrieval-recognition*. Further analysis of the information requests that were initially classified as reasoning showed that some of these requests were responded to by making multiple inferences. In these requests, it was not possible to characterise the FP towards which the inference was moving. Consider for example the following request: *Can we make the Trent 500 IGB sump from jethete?* This request expresses the intent to move from a form (IP: jethete sump) towards one or more undefined issues by making inferences. Hence, a new response process type was identified and termed *deliberation*. Table 3 presents the final list of response processes.

Table 3. Response process category

TYPE	DESCRIPTION
Retrieval-recognition	Retrieval-recognition entails finding and returning information. The response to a retrieval-recognition request is data, information or logically structured information. Ex.: *What material does the Trent 800 use for this part?*
Reasoning	Reasoning entails making an inference. The response to a reasoning request is logically structure information. Ex.: *How can I retain the seal in place?*

Deliberation	Deliberation entails following paths of inference and weighing arguments. The response to a deliberation request is a network of requests, responses and arguments. Ex.: *Can we increase the outer diameter of the Trent 900 shroud tube?* *How much oil does the Trent 900 scavenge if the out diameter of the shroud is increased by 2mm?* *What is the impact of increasing the outer diameter of the shroud tube on the lower splitter fairing design?*

The way the *objective*, *subject* and *response process* categories were used to classify the data deserves a special note. The requests formed to revisit existing solutions (as opposed to those to develop new solutions) can be responded to either by reasoning and deliberation or by retrieval-recognition depending on the knowledge of the questioner. When classifying the data, it was assumed that these requests were always responded to by reasoning and deliberation. This assumption supposes that the questioner did not have the knowledge to answer them by retrieval-recognition.

5. Analysis of the data sets

The data sets from the diary study and the observations were analysed using the categories developed and presented in the previous section. Tables 4, 5 and 6 present the distribution of the requests in the types of the *objective, subject* and *response process* categories.

Table 4. Objective statistics

	DIARY STUDY			OBSERVATIONS		
Objective	**Instances**	**% of total**		**Instances**	**% of total**	
Information	125	51		67	27.9	
Confirmation	23	9.4	71.1	50	20.7	49.4
Comparison	4	1.7		2	0.8	
Constructive generation	13	5.3		26	10.7	
Explanatory generation	30	12.2	37.9	25	10.4	50.6
Analysis	5	2		11	4.6	
Analysis/Evaluation	41	16.7		57	23.7	
Evaluation	4	1.7		3	1.2	

Table 5. Subject statistics

	DIARY STUDY		OBSERVATIONS	
Subject	**Instances**	**% of total**	**Instances**	**% of total**
Product	139	56.7	163	67.6
Process	106	43.3	78	32.4

Table 6. Response process statistics

	DIARY STUDY		OBSERVATIONS	
Response process	**Instances**	**% of total**	**Instances**	**% of total**
Retrieval-recognition	152	62	119	49.4
Reasoning	61	24.9	76	31.5
Deliberation	32	13.1	46	19.1

The results from the diary study and the observations indicated differences that could be explained by the strengths and weaknesses of the two data collection methods. The results from the observations are discussed here because these provided the most accurate data. The observations found that the objective type more frequently formed was *information* followed by *analysis/evaluation* and *confirmation*. It is noteworthy that the combined type, *analysis/evaluation,* was generated because many requests were identified that were responded to by analysis and evaluation. The analysis of the subject type indicated predominance of *product* over *process*. Among the response types, *reasoning* and *deliberation* were found to be as frequent as *retrieval-recognition*.

6. Implications

Information acquisition is an essential part of engineering design. An observational study in the power systems company where this project was carried out showed that the average number of times per hour a designer formed information requests was 2.3; and that designers can spend up to a quarter of their time in information acquisition [Marsh, 1997]. The importance of quick and accurate provision of information to designers in order to improve the efficiency of engineering processes is therefore crucial. The requests studied in this project accounted for the development from initial design through to operation of evolutionary aerospace products. This research showed the richness of information requests and demonstrated how to characterise them through seven types of objective, two types of subject and three types of response process. After the analysis of the two data sets, the researcher asked himself the following question: *How could the designers have been better supported in answering their information requests?* This question is now discussed, focussing on the types of the response process category and referring to the types of objective category.

In many manufacturing organisations, the information to answer retrieval-recognition requests can be accessed from PDM, CAD, standards and material databases. Automatic searches from these large databases are effective if precise descriptions of a subject are known, i.e. keywords. Indexing of and retrieval from large bodies of information and knowledge is still a major issue. Reasoning and deliberation requests were formed: (1) to develop new solutions; and (2) to revisit existing solutions. The information to answer reasoning requests to develop new solutions cannot be obtained from databases. Knowledge-based systems have attempted to simulate the reasoning required to accomplish *constructive generation,* but without much success. Methods to stimulate creativity and actively promote interactions with experienced designers need to be encouraged in order to support designers answering such requests. Not surprisingly, *analysis* and *evaluation* played a significant role in the design process. Designers can use CAD, FEA, stress and thermal models to analyse and evaluate their solutions. However, a significant proportion of these requests arose in the preliminary design stage. Preliminary analyses and evaluations involve a mental investigation of the causal consequences of a solution. The ability to analyse carefully and evaluate a solution prior to implementation was identified as behaviour typical of experienced designers. Hence, promoting interactions with experienced designers should be encouraged. The information to answer reasoning requests to revisit existing solutions can be obtained from databases. Attempts to model *explanatory generation* in the context of design automation have been fairly successful. Automatic search of the information to answer these requests requires an explicit mapping of the relationships between design solutions and functional descriptions. Considerations similar to those proposed for the reasoning requests can also be made for the deliberation requests. However, the information to answer deliberation requests can only be obtained by forming networks of requests, responses and arguments related to the initial requests. This makes deliberation requests more difficult to support than reasoning ones.

7. Conclusions

A review of the literature found that current classifications of information requests were too simple and incomplete. The need to develop a deeper understanding of the nature of information requests and searches was identified as a prerequisite to improving the support that can be provided to designers. In order to contribute to this understanding, a research approach was designed integrating an ethnographic participation with a diary study and observations with shadowing. The ethnographic participation generated a deep understanding of information requests and searches in industry. The diary study provided an opportunity to capture data in real time without the presence of the researcher. The observations were used to capture data at first hand. The observations, not surprisingly, provided the richest data. This paper showed that the *objective*, *subject* and *response process* categories allowed the key differences in the nature of information requests to be characterised. The analysis of the data sets indicated that around 28% of the requests formed by designers do not indicate an objective, and 22% indicate low level objectives like confirmation and comparison. These requests are responded to by retrieval-recognition. Around 50% of the requests indicated high level objectives like constructive generation, explanatory generation, analysis and evaluation. These requests operate at a higher level of design thinking; are responded to by more complex response processes like reasoning and deliberation; are formed to develop new solutions as well as to revisit existing ones; and enable the direct progression of products and processes.

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