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Characterising the information requests of aerospace engineering designers

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Abstract During product development, engineering designers raise several information requests that make them search through human and documentary sources. This paper reports research to characterise, in detail, these requests for designers working in a major aerospace engineering company. The research found that at a high level, a distinction can be made between requests to *acquire information* and to *process information*. The former are raised to access design and domain information. The latter, instead, are formed to define designs. For researchers, this study extends existing knowledge of information requests by characterising key differences in their nature and explaining how they are used in the design process. For practitioners, these findings can be used as a basis to understand the diverseness of information requests and how to channel efforts to support designers in information seeking. In particular, the research indicates that a strategy to support designers should enable the development of engineering communities that share information effectively and the introduction of techniques that facilitate the documentation of information.

Keywords Information requests · Problem-solving · Reasoning · Aerospace engineering design

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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 life cycles and reduced costs. It is known that designers can spend up to a quarter of their time in information acquisition and provision (Marsh 1997). Information is used by designers for a variety of purposes including making sense of past designs, understanding problems, proposing new design solutions, resolving conflicts, negotiating constraints and making decisions (Wasiak et al. 2010). Ensuring that designers find satisfactory answers to their information requests in the shortest time is a key issue to streamline design activities. Previous work found that requests are used to satisfy basic information needs as well as to drive more sophisticated aspects of design inquiry (Eris 2004). However, a review of existing studies indicated that information requests were not studies systematically. In order to improve the support given to designers, it was judged important to develop a deeper understanding of the characteristics of information requests. Therefore, research was undertaken with the aim to characterise the *requests* formed when designing that make engineering designers search through *external* sources. External sources are defined as sources outside of the designer. They include human (e.g. colleague) and documentary sources (e.g. report, drawing, database, book and notebook) in the design environment and exclude the information stored in human memory. Three specific research questions were established to guide the research: (1) What characterises the requests formed by engineering designers? (2) How can a comprehensive classification of requests be developed? and (3) What key types of request do engineering designers form? 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 and requirements (Kuffner and Ullman 1991; Court 1995; Eris 2002). The work reported in this article is part of a wider investigation, which looked also into the searches undertaken to find answer to information requests. The research to address this aim is reported in Aurisicchio et al. (2010).

2 Literature

2.1 Classifications of information requests

Four empirical studies to characterise information requests were reviewed in detail with the aim of understanding their methodological approaches and contributions (Kuffner and Ullman 1991; Gruber and Russell 1992; Baya 1996; Eris 2002). Other studies were reviewed but not analysed further as the classifications proposed either had very low granularity and lacked depth (Heisig et al. 2010), or were not supported by adequate examples (Vijaykumar and Chakrabarti 2008; Robinson 2010). The research presented in the chosen studies was largely conducted in laboratory environments using verbal protocol analyses. As such, neither the effects of social and situational factors on the design process nor the complexity of technical design in industry were taken into account.

The classifications proposed in the four studies are shown in Table 1. The first three classifications were derived analysing questions and conjectures extracted from verbal protocols collected during *individual* design activities (Kuffner and Ullman 1991; Gruber and Russell 1992; Baya 1996). Overall, the classes proposed by Kuffner and Ullman, and Gruber and Russell were found to be flat in the sense that they do not indicate an underlying structure. Differently, the classes proposed by Baya are put in the context of the overall design activity by other classification types, part of his Information Handling Framework. As an example, one of these, termed Informational Activity, consists of three dimensions, namely generate, access and analyse. This aspect of Baya's framework was judged of interest for this investigation and important to advance current understanding of information requests.

Eris, by expanding existing knowledge of questions by Lehnert (1978), Graesser and McMahen (1993) and analysing verbal protocols collected during *group* design

Table 1 Classes in four classifications of information requests

Nature **Kuffner and Ullman (1991)**	**Question type** **Gruber and Russell (1992)**	**Descriptor** **Baya (1996)**	**Question type** **Eris (2002)**
Location	Requirements	Alternative	Request
Construction	Structure/form	Assumption	Verification
Purpose	Behaviour/operation	Comparison	Definition
Operation	Functions	Construction	Example
	Hypothetical	Location	Feature Specification
	Dependencies	Operation	Concept Completion
	Constraint checking	Performance	Quantification
	Decisions	Rationale	Disjunctive
	Justif. and evalu. of alternatives	Relation	Comparison
	Justif. and explan. of functions	Requirement	Judgemental
	Validation explanations	Miscellaneous	Interpretation
	Computations on model		Procedural
	Definitions		Causal Antecedent
	Other design moves		Causal Consequent
			Rationale/ Function
			Expectational
			Enablement
			Proposal/ Negotiation
			Enablement
			Method Generation
			Scenario Creation
			Ideation

activities, proposed a classification with a finer granularity of information classes than in the other studies (Eris 2002, 2004), see Table 1. The classes are divided into two groups at different conceptual level, namely a high-level group and a low-level group. In Table 1, the low-level classes termed ‘Other’ are indicated using a *white* background, whereas the high-level classes use a *grey* background of different tonalities. The high-level classes were described by Eris as conceptually closer to what the questioner intended. Answering these questions is expected to require more knowledge than low-level classes. The high-level classes were divided into three subgroups termed Judgemental, marked in *grey* 10 %; Deep Reasoning Questions (DRQ), marked in *grey* 20 %; and Generative Design Questions (GDQ), marked in *grey* 30 %. The DRQ subgroup aims at understanding facts and is associated with convergent-thinking, whereas the GDQ subgroup aims at creating possibilities from facts and is associated with divergent-thinking. The GDQ subgroup, developed by Eris (2002, 2004), includes five classes that are typical of generation in design. Two of these classes were found to be conceptually identical, namely *Enablement* and *Method Generation*. Similarly to the work of Baya (1996), Eris investigated the role of questions in three design activities, namely conceptualisation, implementation and assessment (Eris 2002, 2004). Although Eris’s classification indicates a structure, it only partly explains how the different question types relate to each other, and how and when they are used in the design process. This means that a model is visible behind the classes of question but it is not formalised.

Deeper analysis of Eris’ classification found that it subsumes four important *characteristics* of requests. The first is the *objective* of a request as it can be seen from the classes ‘*verification*’, ‘*comparison*’ and ‘method *generation*’ indicating, respectively, the objectives to verify, compare and generate. The second characteristic is the *subject* of a request as it can be seen from the classes ‘method generation’ and ‘procedural’ indicating whether the subject is a product or a process. The third characteristic is the *response process* as it can be seen from the *lower* level questions (white) and the ‘Deep *Reasoning* Questions’ (grey 20 %) indicating that information requests are answered using different response processes. The fourth characteristic is the *response type* as shown by the classes ‘*feature* specification’, ‘*concept* completion’ and ‘*method* generation’ indicating that the responses can be features, concepts and methods.

Overall, it was concluded that the classifications proposed in these studies were incomplete and there was a need to develop a deeper understanding of information requests. In particular, the analysis indicated that a new study should give careful consideration to the characteristics of information requests identified reviewing Eris’ work. Among these, the *objective* characteristic suggested investigating the role of information requests in the *problem-solving* process, whereas the *response process* characteristic that of the *reasoning* process.

2.2 Problem-solving in design

The engineering design process can be viewed as a human problem-solving activity. Models of problem-solving have been proposed, among others, by March (1984), Ullman (1988), Gero (1990), see Table 2.

Table 2 shows a common pattern across the models, consisting of three main activities, namely: (1) generation, (2) analysis and (3) evaluation. The models differ in the detail with which the three main activities were characterised (for example Ullman’s model indicates a hierarchy of activities); in the additional activities addressed (for example March’s model does not indicate activities prior to generation and after evaluation); and in the terminology employed (for example evaluation is regarded differently). In this research, the activities undertaken in problem-solving were considered to follow the pattern: *generation–analysis–evaluation*. These activities indicate specific objectives (intents) that can be identified in information requests. The example of the design of a dishwasher for a sailing boat, originally proposed by Roozenburg and Eekels (1995), is used here to illustrate this point. The function to be realised is unbroken, dirty dishes must become unbroken, clean dishes, with the help of sea water and under rough swell and large angles of inclination of the sailing boat. A request such as *How can the dishes be kept in a horizontal position?* is generally employed to *generate* a solution. After the idea of cardanic suspension is

Table 2 Problem-solving activities

		Generation	Analysis	Evaluation	
March (1984)		Description	Prediction	Evaluation	
Ullman (1988)		Generation (selection, creation)		Evaluation (calculation, simulation and comparison)	Decision (acceptance, rejection, suspension, patching)
Gero (1990)	Formulation	Synthesis	Analysis	Evaluation	Documentation

generated, a request such as *What position will the dishwasher adopt if suspended cardanically?* is employed to *analyse* the solution. When the position of the dishwasher is predicted to be horizontal, a request such as *Does the predicted position meet the requirement?* is employed to *evaluate* the idea of a cardanic suspension. If the solution is found to be satisfactory, further work to embody this concept can be undertaken.

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), known as the premise, to a final proposition (FP), known as the conclusion (Roozenburg 1993). Some *information requests* express the intent to move from an IP to a FP by reasoning. Generally, the forming vocabulary of these requests contains a description of the IP, while the FP is described by the response to the request. Consider for example a request such as *How can the dishes be kept in a horizontal position?* The IP of this request is *keeping the dishes in a horizontal position*, whereas the FP is the answer to this request, that is, *a cardanic suspension*. This is an example of a request to *generate* a solution to a design problem, but information requests can express also the objective to *analyse* and *evaluate*, see Sect. 2.2. The reasoning types required to answer these information requests are expected to differ depending on the experience of the questioner, the nature of the problem and the objective of the problem-solving activity. This issue suggested reviewing the literature on reasoning to gain insights on how to characterise information requests.

In design research, models of the reasoning process have been proposed by March (1984), Coyne (1988), Roozenburg (1993), Tomiyama et al. (2003). The model proposed by Roozenburg was adopted because its elements were found to be at an adequate level of description for the purpose of this research. In this model, 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,* a move from form to predicted behaviour. Reduction has three different forms: (1) induction, (2) abduction and (3) innoduction. These are all forms of plausible, non-demonstrative 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: $p1 \rightarrow q1; p2 \rightarrow q2; \ldots$). 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 (Roozenburg 1993). In design, this type of reasoning appears to support, for example, *evaluation*, a move from predicted behaviour to intended behaviour (March 1984). 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) (Roozenburg 1993). In design, this type of reasoning supports, for example, *generation to explain existing solutions*, a move from intended behaviour to form. 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) (Roozenburg 1993). In design, this type of reasoning supports, for example, *generation to construct new solutions*, a move from intended behaviour to form.

This literature review revealed four main reasoning types and provided examples of how they can support the three problem-solving objectives, that is, generation, analysis and evaluation. Abduction and innoduction appear to be used to explain existing solutions and to construct new solutions. These two reasoning types suggested investigating in detail generative information requests with the aim of identifying the differences in their structure or forming vocabulary. The examples presented in this review do not aim at establishing unique links between the reasoning types and the objectives. In fact, each objective is expected to be accomplished by more than one reasoning type, for example generation can be undertaken by deduction, abduction and innoduction.

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 fields 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 Methodological approach

The practical approach taken aligns with the design research methodology developed by Blessing and Chakrabarti (2009). This methodology consists of four main stages: criteria, descriptive study I, prescriptive study and descriptive study II. The research presented in this article focuses on the first and the second stage of the methodology. In the first stage, a range of criteria were identified, such as the frequency with which relevant answers to information requests are found, and a network of causal influences linking back to overall success criteria of improving the design process. In the second stage, analyses of the design process were carried out to discover the relationships between the criteria and the design process. In this case, empirical research was undertaken to investigate the nature of the information requests.

The review of previous empirical studies of information requests (Aurisicchio 2005) indicated, among others, the need to: (1) consider approaches beyond laboratory experimentation in order to recognise design as a context-bound activity situated in commercial organisations with their own practices, structures and social interactions (Bucciarelli 1984, 1998); and (2) provide the researcher with experience of engineering design in order to acquire a deeper understanding. Based on these indications, an approach was designed integrating ethnographic participation with analytical empirical methods (Langdon et al. 2003). Ethnography was employed as part of the first research phase in order to generate insights, see Fig. 1. Towards the end of this phase and in parallel with the ethnographic research, a diary study was undertaken. Observations with shadowing were employed as part of the second research phase and spaced by 12 months, see Fig. 1. Part of this time was necessary to analyse the diaries and the interviews, and use the results to inform the next phase of the research; the remaining time was, instead, used to negotiate the observational study with the managers, identify the participants and schedule the work. Among the twelve participants to the diary study and the ten participants to the observational research, none was involved in both the investigations to avoid overloading them. From Fig. 1, it can be seen that pilots were carried out before the main studies to validate the methodological approach and the quality of the data gathered. The employment of three different types of study enabled the data to be triangulated and thus increase the objectivity of the overall results. All the studies were conducted in a department of the collaborating company focusing on the design of transmissions, structures and drives of gas turbines for aerospace applications.

3.1 Ethnographic participation

During the 9-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 precise definition of the aims and the selection of the subsequent data collection methods. Overall, this study enabled the researcher to be embedded within the social and technical context, and it was more useful in creating the conditions to gather and interpret the data collected through the subsequent methods, rather than in capturing primary data (Langdon et al. 2003).

3.2 Diary study

Diary studies are receiving increasing attention as a research method to understand design work (Dorst and Hendriks 2001; MacGregor et al. 2001; Wild et al. 2010) including new applications where designers have been provided with PDAs (Robinson 2010). The method requires the participants to self-report about an experimental situation and it is subject to the willingness of the participants to contribute, and to self-selection bias due to the commitment required (DeLongis et al. 1992). Diary studies are intrusive, as extra work is required on each participant's part.

The 5-week diary study employed in this research was selected because it allowed the involvement of many individuals and it facilitated the gathering of information requests over an extended time period without the presence of the researcher. In order to increase the response rate, and to make it easier and more enjoyable, it was decided to limit as much as possible the amount of information to be recorded. Due to the need to gather data about frequent but unpredictable episodes, an event contingent diary study was used. This is considered less intrusive than signal or interval contingent diary studies.

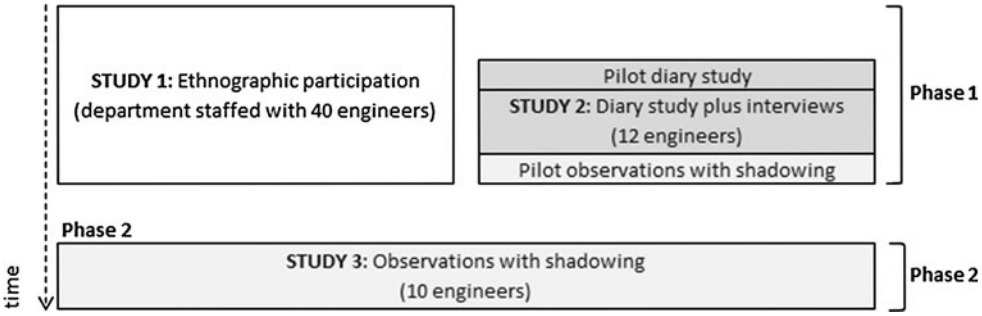


Fig. 1 Methodological diagram

Twelve engineers from the collaborating design department agreed to self-report their requests whenever they occurred. The sampling process took into account the differences of experience and technical competence of the engineers as well as the projects in progress and their stage of completion. The researcher first planned the sampling process and then negotiated it and agreed it with managers. The tight schedules of the design department imposed many constraints. The experience of the twelve participants to the main study was on average of 7.9 years with a SD of 5.3.

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. The requests captured per participant varied from a minimum of three in 2 days to a maximum of fifty-four in 15 days. The participation varied greatly, and it was significantly below expectations with the consequence that the data set was considered not fully reliable. In addition, the methodological objectives to characterise in detail information requests and collect data over a time period of 5 weeks were not met. Although the data could not be used as intended, the diary study provided enough data to conduct an exploratory analysis.

The design tasks studied were variant designs, that is, the work usually involved incremental innovation to extend existing product solutions. The tasks were mostly undertaken during stage 2 (full concept definition) and stage 3 (propulsion system realisation) of the product development process used in the collaborating company (Moore 1997). In stage 2, concepts are further developed and detailed plans are prepared for project implementation against a hardening business opportunity, whereas in stage 3, the plans are implemented including the detailing of the designs, the manufacture of prototypes, verification, certification and the manufacture of production engines.

3.3 Observations with shadowing

The observations provided an opportunity to capture at first-hand information requests. The method is rather intrusive as the researcher tends to spend several hours with the participant. In this study, the participants were asked to think aloud only to express their information needs. The possibility of adopting thinking aloud for an observation of 7 h was considered, but found too burdensome. The participants were not asked to explain their cognitive processes therefore reducing the risk to change the underlying process (Ericsson and Simon 1993). Thinking aloud only appears to require additional time for subjects to complete the verbalisation.

Five engineers were observed for 4 h each as part of a pilot investigation and other ten were observed for 7 h each as part of the main study. The sampling process followed the same approach used for the diary study. The experience of the ten participants to the main study was on average of 8.3 years with a SD of 7.3. Prior to the start of an observation, each participant was asked to follow his or her daily schedule and to think aloud to describe any information request requiring an external search. The observations were followed by interviews. Overall, a total of 241 original requests were collected. The requests captured per participant were on average 2.5 per hour with a SD of 1.1. The observations provided the richest data and the greatest number of insights. The design tasks studied during the observations were also variant designs. Differently from the diary study, the tasks were mostly undertaken during stage 1 (new project planning) and stage 3 (full concept definition) of the product development process (Moore 1997). In stage 1, a business need is identified and new technical concepts are matched to new market opportunities.

4 Development of the information request categories

Information *requests* were studied within their *context* and together with the *searches* to answer them. The characteristics of these three aspects were described using a framework composed of twelve categories and their dependent types, see Table 3. The framework includes a group of categories for each aspect: (1) context group (three categories), (2) request group (six categories) and (3) search group (three categories). Under each category, the context of a request, the request itself and its associated search are characterised as one of a number of predefined types.

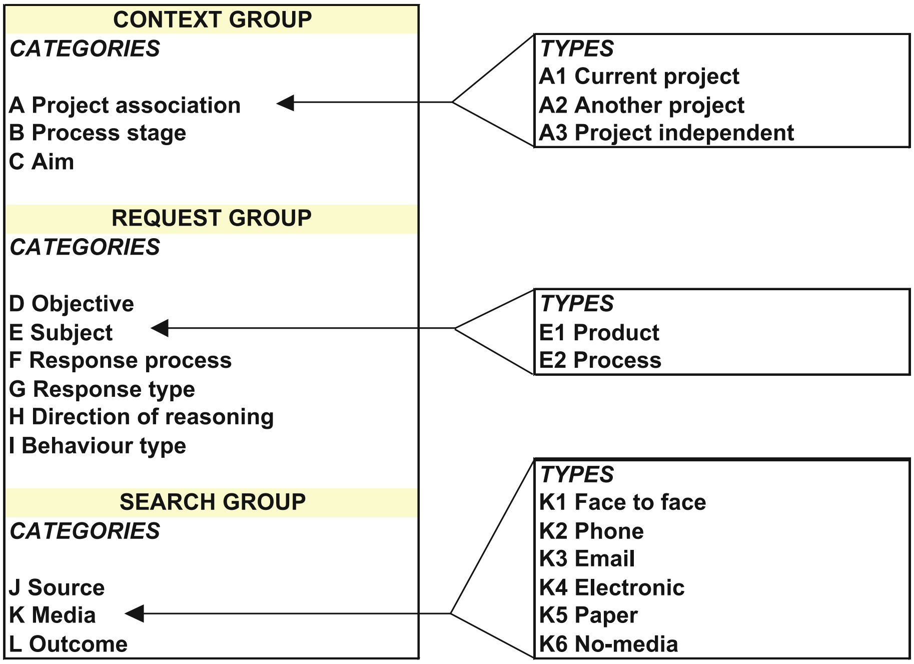
The framework was developed through an iterative approach that consisted in repeating the stages of data gathering, data analysis and testing, and results presentation. The categories were derived from an analysis of the literature and empirical research on data sets that accounted for the development of a product from the initial design through to operation in-service, and the sequential and parallel development of multiple projects.

The article focuses now on the *request group* of categories as they were key in addressing the research aim to characterise information requests.

4.1 Categories D, E, F and G

The *objective* of an information request describes the intent of the designer who raised the request and, therefore, that of the design activity in progress. Analysing current

Table 3 Framework structure: three groups of categories



CONTEXT GROUP

CATEGORIES

A Project association
B Process stage
C Aim

TYPES
A1 Current project
A2 Another project
A3 Project independent

REQUEST GROUP

CATEGORIES

D Objective
E Subject
F Response process
G Response type
H Direction of reasoning
I Behaviour type

TYPES
E1 Product
E2 Process

SEARCH GROUP

CATEGORIES

J Source
K Media
L Outcome

TYPES
K1 Face to face
K2 Phone
K3 Email
K4 Electronic
K5 Paper
K6 No-media

classifications of information requests and the two data sets, it became evident that some requests do not indicate an objective beyond the need to obtain information, whereas others indicate specific objectives such as confirmation, comparison, generation, analysis and evaluation. Consider, for example, the difference between a request to obtain information, for example *What is the coefficient of thermal expansion of this material?* and a request to analyse a solution, for example *What could be the movements of this part?* Among the requests indicating an objective, it was found that some were formed to pursue low-level objectives, for example confirmation and comparison, whereas others to pursue high-level objectives typical of problem-solving, for example generation, analysis and evaluation. Low-level and high-level objectives are conceptually distinct and operate at different levels of problem-solving. Consider, for example, the difference between a request to compare operational parameters, for example *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, for example *How much should the diameter of the shroud of the Trent 900 radial drive shaft be increased to scavenge oil adequately?*

Based on this understanding, a preliminary list of objectives was proposed including *information*, *confirmation*, *comparison*, *generation*, *analysis* and *evaluation*. Further analysis showed that this list of objectives still did not permit the characterisation of important differences in information requests. One issue related to the *generation* objective. In design, generation entails moving from an intended behaviour to a form. Designers raise information requests to move from intended behaviour to form, both to develop new solutions and to revisit existing solutions (Eris 2002, 2004). 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, for example *How can we flood the oil in the Trent 900 gearbox?* Assume now that the same designer, before answering this information request, forms three further requests to revisit existing concepts to flood oil, for example *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?* The first of these four requests is the only one that can lead to the construction of a new solution, the others having been raised to explain existing solutions. Among the last three requests, the first two ask what concepts were used in past projects, whereas the last one asks what concepts were used in other product areas. It is interesting that in the final request example, the reasoning moves away from the specific situation on which the designer is working to look for new product areas where that particular

Table 4 Objective category (D)

Type	Description
D1 Information	The request wants to obtain information but does not indicate an objective. Ex.: *What material does the Trent 800 use for this part?*
D2 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?*
D3 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?*
D4 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?*
D5 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?*
D6 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?*
D7 Evaluation	The request wants to establish: (1) 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 (2) the degree of merit of a number of solutions by relative comparison. Ex.: *Is the stress in the HPIP hub acceptable?*

Table 5 Subject category (E)

Type	Description
E1 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 and product requirements. Ex.: *How can I retain the seal in place?*
E2 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 and analysis and management. Ex.: *Where could I best start this task?*

Table 6 Response process category (F)

Type	Description	
F1 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?*	
F2 Reasoning	Reasoning entails making an inference. The response to a reasoning request is logically structured information	
	Ex.: How can we flood the oil in the Trent 900 gearbox?	To move from an IP (flooding/distributing oil) to a FP (physical concept to flood/distribute oil) by reasoning.
F3 Deliberation	Deliberation entails following paths of inference, considering 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?	To move from an IP (increase of the outer diameter) towards a FP (yes or not) by making inferences and considering issues (the process is undefined)
	How much oil does the Trent 900 scavenge if the outer diameter of the shroud is increased by 2 mm?	To move from an IP (increase of the outer diameter) to a FP (quantity of oil scavenged) by reasoning
	What is the impact of increasing the outer diameter of the shroud tube on the lower splitter fairing design?	To move from an IP (increase of the outer diameter) to a FP (interface with lower splitter fairing) by reasoning

intended behaviour was satisfied. Table 4 presents the final list of objectives derived from the analysis.

The *subject* of an information request describes the major object of interest, see Table 5 for the list of subjects identified.

The *response process* of an information request describes the cognitive process involved in finding an answer. Initial data analysis suggested to distinguish the requests responded to by finding and returning information from those responded to by making an inference from an initial proposition (IP) to a final proposition (FP) (or transforming information). In order to characterise this difference, two types of response process were identified and termed *retrieval-recognition* and *reasoning*, see Table 6.

Further data analysis showed that some requests are responded to by making an inference and others by making multiple inferences, considering and weighting arguments. In order to characterise this difference, a new type of response process was identified and termed *deliberation*, see Table 6 and consider the example of deliberation information request provided. In this request, the designer considers increasing the outer diameter of the shroud tube following a possible problem with the oil scavenge capability in the Trent 900 radial drive shaft to its shroud. The example shows that in order to carry out the deliberation process, the designer forms first a deliberation request and then a network of reasoning requests.

At the time a deliberation request is formed, the deliberation process is still to be undertaken. In this initial situation, the questioner is not focused on a specific issue and his or her reasoning does not indicate a direction. This means that the questioner is starting to consider the issues relevant to the subject of the deliberation as well as to form the requests necessary to develop a view. In these requests, it was not possible to characterise either both the FP towards which the inference was moving and the required process or the process only. Table 6 presents the final list of response processes.

The *response type* of an information request describes its answer, see Table 7 for the list of response types identified. The first four types are fully textual. However, a difference can be made between *boolean*, *numerical value* and *symbol*, which are basic types and *statement*, which is a compound type composed of the previous three types as well as of words. The final three types are also compound as they are inclusive of both textual and graphic information.

Table 7 Response type (G)

Type	Description
G1 Boolean	The request expects to obtain one of two possible values, for example yes or no
G2 Numerical value	The request expects to obtain a figure, for example dimension
G3 Symbol	The request expects to obtain a letter, figure or other character or a combination of some of them, for example material identifier
G4 Statement	The request expects to obtain a string composed of booleans, numerical values, symbols and words
G5 Configuration	The request expects to obtain a statement and graphic information to describe a solution, for example the form/structure of a feature, part or assembly
G6 Layout	The request expects to obtain a statement and graphic information to describe the disposition of a solution, for example the way the form/structure of a feature, part or assembly is arranged
G7 Source	The request expects to identify a collection of statements and graphics that supply information or evidence, for example report and drawing

4.2 Categories H and I

The final two categories were developed to characterise the *information transformation* of the *requests* involving *reasoning* about the *product*. The research investigated the possibility of characterising the initial proposition (IP) and the final proposition (FP) of these requests through descriptions of a product in terms of *behaviour* and *form or structure*. Initial analysis using this approach showed that the transformation undertaken by a product reasoning request could be described through its objective and distinguished by the problem type. Consider now three examples of product reasoning request and their description:

- *Where can I bring the oil jet in to best feed the bearing cage?* This request was raised by a designer, working on the radial drive shaft bearings, to *design* the best location for the oil feed to the bearing cage. The IP of this request is *where to bring in the oil jet to best feed the bearing cage* (intended behaviour) and the FP is a *spatial position* (form). This request has, therefore, the objective to *generate* a *design* solution;
- *What caused the oil leak?* This request was raised by a designer to *diagnose* the cause of a malfunction that emerged during engine development. The IP of this request is *oil leak* (observed behaviour) and the FP is a problem in the *oil nozzle orifice* (form). This request has, therefore, the objective to *generate* a *diagnosis* solution;
- *What is that part doing?* This request was raised by a designer to *assign a function* to a part that he was not familiar with by looking at its drawing. The IP of this request is *part* (form) and the FP is its *function* (intended behaviour). This request has, therefore, the objective to *generate* a *functional assignment* solution.

Prior to this work, the above requests were classified as types of generation in the *objective* category. However, characterising the information transformation enabled to

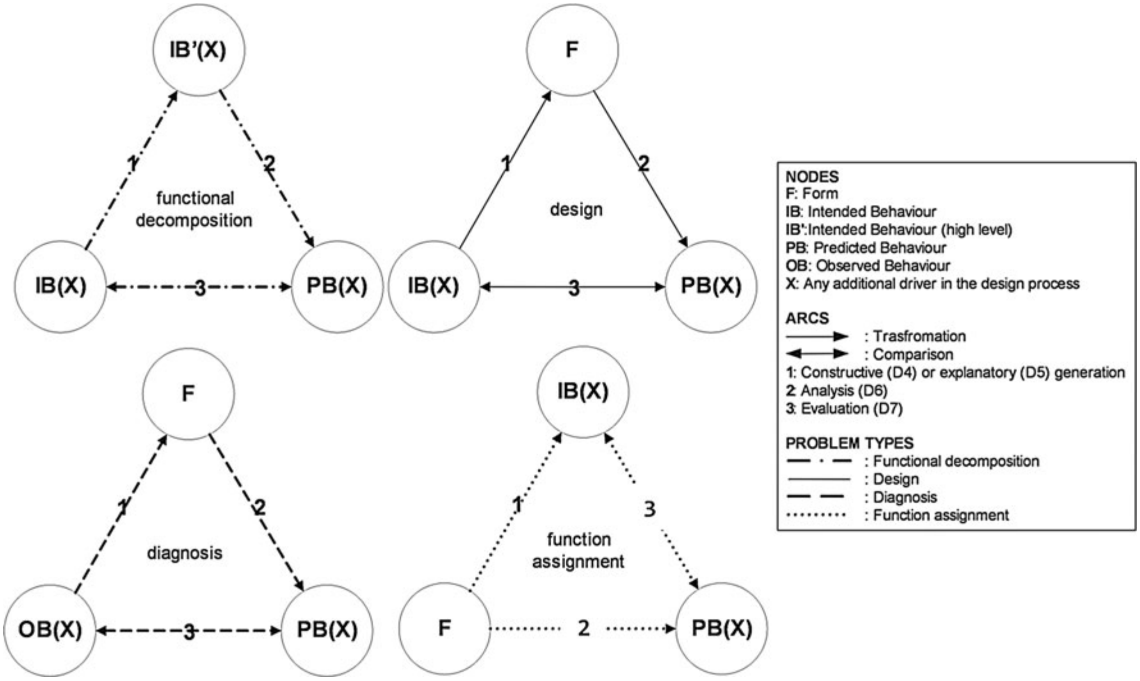


Fig. 2 Problem-solving models

describe both the objective and problem type of these requests. These results suggested suspending the data analysis to follow a new research approach consisting first in defining simple problem-solving models and then in evaluating whether product reasoning requests could be used to describe them. Inspired by the work of Gero (1990), Gero and Kannengiesser (2004)) on modelling *design* using the concepts of function, behaviour and structure, the authors developed four models corresponding to the problem types identified during data analysis, see Fig. 2.

Each model consists of a graph where *arcs* link *nodes*. The nodes describe different states of the developing product through three classes of variables: (1) form or structure variables (describe the components of an artefact and their relationships); (2) behaviour variables (describe the whole complex of transformations that occur to an artefact during its use); and (3) X variables (describe any additional issue driving the design process). The arcs describe different transformations linking the nodes.

Each model is composed of three transformations that follow a common problem-solving pattern consisting of generating, analysing and evaluating solutions. The transformations for each problem type are briefly outlined below:

- *Functional decomposition*: (1) generation transforms an intended function (IB(X)) into a function structure (IB'(X)); (2) analysis derives a predicted behaviour (PB(X)) from the function structure (IB'(X)); and (3) evaluation compares the predicted behaviour (PB(X)) against the initial intended function (IB(X)). This model is in line with the findings by Bracewell and Sharpe (1996).
- *Design*: (1) generation transforms a function (IB(X)) into a form (F); (2) analysis derives a predicted behaviour (PB(X)) from a form (F); and (3) evaluation compares the predicted behaviour (PB(X)) against the initial function (IB(X)). This model is in line with the findings by March (1984), Gero (1990), Gruber (1996).
- *Diagnosis*: (1) generation transforms an unsatisfactory observed behaviour (OB(X)) into a cause (F); (2) analysis derives a predicted behaviour (PB(X)) from a cause (F); and (3) evaluation compares the predicted behaviour (PB(X)) against the initial problem (OB(X)). This model is in line with the findings by Patel and Ramoni (1997) in the medical field.
- *Function assignment*: (1) generation transforms a form (F) into a function (IB(X)); (2) analysis derives a predicted behaviour (PB(X)) from a form (F); and (3) evaluation compares the predicted behaviour (PB(X)) against the hypothesised function (IB(X)). This model is supported by an empirical study of the differences in reading schematic drawings of mechanisms by expert and naive mechanical designers conducted by Waldron et al. (1987) and is in line with the findings from Kroes (1998).

After modelling the problems, a new systematic analysis of the data was performed. Many of the information transformations in the models could be described through the requests in the data sets and were formalised into two categories termed *direction of reasoning* and *behaviour type*. The first category describes part of the information transformation to answer a request, while the second contributes to fully characterise it, see Tables 8 and 9.

These two categories, unlike the previous four, were designed to be used together. By combining their types, several directions of reasoning are described, see Table 10.

Table 10 shows that eight directions of reasoning pursuing different objectives and typical of specific problem types were identified. It is noteworthy that the direction H7-I4 was generated to characterise process reasoning requests and the direction H7-I5 non-reasoning requests, that is, retrieval-recognition and deliberation requests. Using this new category, the information requests previously presented are characterised as follows: *(1) Where can I bring the oil jet in to best feed the bearing cage?* [intended behaviour to form (H3-I1)]; *(2) What caused the oil leak?* [observed behaviour to form (H3-I3); *(3) What is that part doing?* [form to intended behaviour (H5-I1)].

Table 8 Direction of reasoning (H)

Type
H1 Market need to specification
H2 Behaviour to behaviour
H3 Behaviour to form
H4 X to form
H5 Form to behaviour
H6 Form to X
H7 No value

Table 9 Behaviour type (I)

Type	Description
I1 Intended	Describes a behaviour that is intended to be predicted from a form
I2 Predicted	Describes a behaviour that is predicted from a form
I3 Observed	Describes a behaviour that is observed from a form
I4 Procedural	Describes a procedure
I5 No value	Does not describe a behaviour or procedure

Table 10 Defined direction of reasoning (H–I)

Code	Description	Objective	Problem type
H2-I1	IB to IB	Gen	Functional decomposition
H3-I1	IB to F	Gen	Design
H4-I5	X to F	Gen	Design
H5-I1	F to IB	Gen	Function assignment
H3-I3	OB to F	Gen	Diagnosis
H5-I2	F to PB	Ana	Design, diagnosis, function assignment
H6-I5	F to X	Ana	Design
H2-I2/I1	PB to IB	Eva	Design, functional decomposition, function assignment
H7-I4	Procedural	Gen, Ana, Eva	Process
H7-I5	No value	–	–

4.3 Discussion of the categories and summary

This section presented six categories to model information requests as part of an empirical *framework* for information acquisition. Such a framework characterises an information *request* in greater detail than the *context* of a request and its associated information *search*.

The *request group* categories are the result of a bottom-up analysis of the data sets that involved several iterations. The categories were developed starting from examples of information requests and using them as basis for the description. During data analysis, this method of classifying information requests was found to be: (1) flexible as it allowed the creation of deeper and more complex knowledge structures by extending the range of types under each category; and (2) practical as it allowed the consideration of single and multiple characteristics of information requests. In the literature, this method is known as faceted classification and is used to classify documents in complex and multi-concept domains (Ranganathan 1963; McMahon et al. 2004).

The *request group* categories differ from the classifications reviewed in Sect. 2.1 in the following ways: (1) each category provides a classification of information requests based on a *single* characteristic (the categories H and I are exceptions); and (2) two or more categories can be used to extract a classification of information requests based on *multiple* characteristics, see Sect. 6.

The *objective*, *response process* and *defined direction of reasoning* categories formalise, more than the others, new knowledge on information requests. The first introduces the concept of requests without an objective, with low-level objectives and with high-level objectives. A key distinction was uncovered through this category between *constructive generation* and *explanatory generation*. The second proposes to distinguish information requests based on the cognitive processes involved in finding answers. In previous research, information requests were classified as deep reasoning; however, a systematic classification depending on the response process was not found in the literature. The third instead led to the development of new understanding on the types of information request raised by designers to solve design and other problem types.

The conceptual understanding gained during data analysis suggests that at a high-level engineering, designers raise requests to *acquire information* and requests to *process information*. The former have low-level objectives like *information*, *confirmation* or *comparison*, are answered through simple response processes like *retrieval-recognition* and aim at accessing design and domain information. Design information describes the requirements of the problem at hand and proposed solutions, while domain information consists of known facts, concepts, laws and theories in the domain of the problem.

The latter have high-level objectives like *generation*, *analysis* or *evaluation*, are answered through complex response processes like *reasoning* and *deliberation*, and aim at accessing problem-solving information. This information often does not exist at the time in which the request is formed. These requests are instrumental for progressing design tasks and the information to answer them is most frequently obtained from human sources.

5 Analysis of the data sets using the six request categories

The distribution of the requests in the types of the categories is presented in Tables 11,12,13,14 and 15. The statistics in these tables do not aim at characterising the distributions with the level of accuracy provided by the use of one decimal place. Percentages with one decimal place are displayed only to avoid a class with one instance having a corresponding percentage of zero, see Tables 14 and 15.

The statistical results (Chi-square test of homogeneity, $\chi^2 < c$, at 0.05 significance level) indicate a difference in the distributions from the diary study and the observations. In particular, the data set from the observations compared to that from the diary study includes more requests to pursue high-level objectives, see Table 11. This difference can be explained in two ways: (1) the tasks studied in the observations were undertaken in stages of the product development process where the design activity is more conceptual, see Sect. 3; and (2) the data were collected first-hand therefore increasing the chances of capturing complex requests. Overall, the results from the observations were considered to provide the most accurate data and, therefore, in the remaining part of this section, the focus is on this data set.

Table 11 Objective statistics

	Diary study – 245			Observations – 241		
D	C	%	CI	C	%	CI
D1	125	51	± 6.3	67	27.9	± 5.6
D2	23	9.4	± 3.7	50	20.7	± 5.1
D3	4	1.7	± 1.6	2	0.8	± 1.1
D4	13	5.3	± 2.8	26	10.7	± 3.9
D5	30	12.2	± 4.1	25	10.4	± 3.8
D6	5	2	± 1.8	11	4.6	± 2.6
D6/D7	41	16.7	± 4.7	57	23.7	± 5.3
D7	4	1.7	± 1.6	3	1.2	± 1.4

χ^2 test of homogeneity: $\chi^2 = 37.8$, $\chi^2 > c$, at 0.05

C count, % per cent of total; *CI* confidence interval at 95 %

Table 12 Subject statistics

	Diary study - 245			Observations – 241		
E	C	%	CI	C	%	CI
E1	139	56.7	± 6.2	163	67.6	± 5.9
E2	106	43.3	± 6.2	78	32.4	± 5.9

χ^2 test of homogeneity: $\chi^2 = 6.1$, $\chi^2 > c$, at 0.05

C count, % per cent of total; *CI* confidence interval at 95 %

Table 13 Response process statistics

	Diary study - 245			Observations – 241		
F	C	%	CI	C	%	CI
F1	152	62	± 6.1	119	49.4	± 6.3
F2	61	24.9	± 5.4	76	31.5	± 5.8
F3	32	13.1	± 4.2	46	19.1	± 4.9

C count, % per cent of total; *CI* confidence interval at 95 %

χ^2 test of homogeneity: $\chi^2 = 8.1$, $\chi^2 > c$, at 0.05

Table 14 Response-type statistics

	Diary study - 245			Observations – 241		
G	C	%	CI	C	%	CI
G1	64	26.1	± 5.5	102	42.4	± 6.2
G2	56	22.9	± 5.3	39	16.2	± 2.0
G3	13	5.3	± 2.8	6	2.5	± 5.0
G4	73	29.8	± 5.7	49	20.3	± 2.8
G5	12	4.9	± 2.7	30	12.4	± 4.1
G6	0	0	± 0.0	1	0.4	± 0.8
G7	27	11	± 3.9	14	5.8	± 2.9

χ^2 test of homogeneity: $\chi^2 = 31.5$, $\chi^2 > c$, at 0.05

C count, % per cent of total; *CI* confidence interval at 95 %

Before presenting these results, it is worth noting that approximately 82 % of the information requests were in the context of a current project, 6 % in the context of another project and 12 % project independent (Aurisicchio 2005). This clearly shows that information requests were predominantly formed to progress aspects of a current project.

The most frequent objective was *information* followed by *analysis/evaluation* and *confirmation*, see Table 11. It can also be seen that the requests without an objective (D1) and with low-level objectives (D2–D3) are nearly equal to those with high-level objectives (D4–D7). This result

Table 15 Defined direction of reasoning statistics

	Diary study – 245			Observations – 241		
H-I	C	%	CI	C	%	CI
H2-I1	2	0.8	± 1.1	0	0	± 0.0
H3-I1	6	2.4	± 1.9	27	11.2	± 3.9
H4-I5	3	1.2	± 1.4	2	0.8	± 1.1
H5-I1	4	1.6	± 1.6	3	1.2	± 1.4
H3-I3	0	0	± 0.0	1	0.4	± 0.8
H5-I2	7	2.9	± 2.1	17	7.1	± 3.2
H6-I5	10	4.1	± 2.5	7	2.9	± 2.1
H2-I2/I1	4	1.6	± 1.6	3	1.2	± 1.4
H7-I4	25	10.2	± 3.8	16	6.6	± 3.1
H7-I5	184	75.2	± 5.4	165	68.4	± 5.8

χ^2 test of homogeneity: $\chi^2 = 14.6$, $\chi^2 > c$, at 0.05

C count, *%* per cent of total; *CI* confidence interval at 95 %

clearly indicates that half of the requests were used to acquire and confirm information, while the other half to solve problems. The analysis of the subject indicates a predominance of *product* over *process* information, see Table 12. This result is not surprising and reflects the fact that the tasks observed were all aimed at defining new geometries. Among the response processes, *reasoning* and *deliberation* together are as frequent as *retrieval-recognition*, see Table 13. This result has to be interpreted in conjunction with that from the objective category in Table 11. It can be seen that the requests without an objective and with low-level objectives were always answered through retrieval-recognition, and the requests with high-level objectives either through reasoning or deliberation. The most frequent response is *boolean* followed by *statement*, *numerical value* and *configuration*, see Table 14. This result means that the majority of the requests required either a yes or a not as an answer. It is important to note that these requests had significantly different characteristics as some were formed to confirm information and others to evaluate (or less appropriately to confirm) designs. Finally, among the defined directions of reasoning, *generation* in design (H3-I2) and *analysis* in design, diagnosis and function assignment (H5-I2) are the types more frequently formed, see Tables 10 and 15. This result indicates that the tasks studied had strong generative and analytical components focusing on the fulfilment of specific behaviours.

6 Extraction of the coding schemes

The need to develop a more comprehensive view on information requests led to the extraction of two coding schemes from the *request group* categories. Before extracting the schemes, a pair-wise Kendal correlation test was carried out on the two data sets to identify whether or not the categories would provide the same information (zero means that the categories are orthogonal and, therefore, do not provide the same information, while one means that the categories provide the same information). The test showed that the correlation was always below 0.5 for all pairs (often considerably below this value), except that for the *objective* (D) and *response process* (F) pair at approximately 0.8, see detailed correlation results in Appendix 1. The D and F pair indicated a high correlation because of the way the data were classified, see Appendix 2. From a conceptual perspective, the two categories clearly provide different information, see again Tables 4 and 6. Overall, the results of the correlation test supported the claim that a classification extracted from multiple categories provides more information than relying only on a single category. Two classifications were extracted and called *coding schemes*.

6.1 First coding scheme

The first coding scheme was extracted from all of the six categories in the *request group*, see Fig. 3.

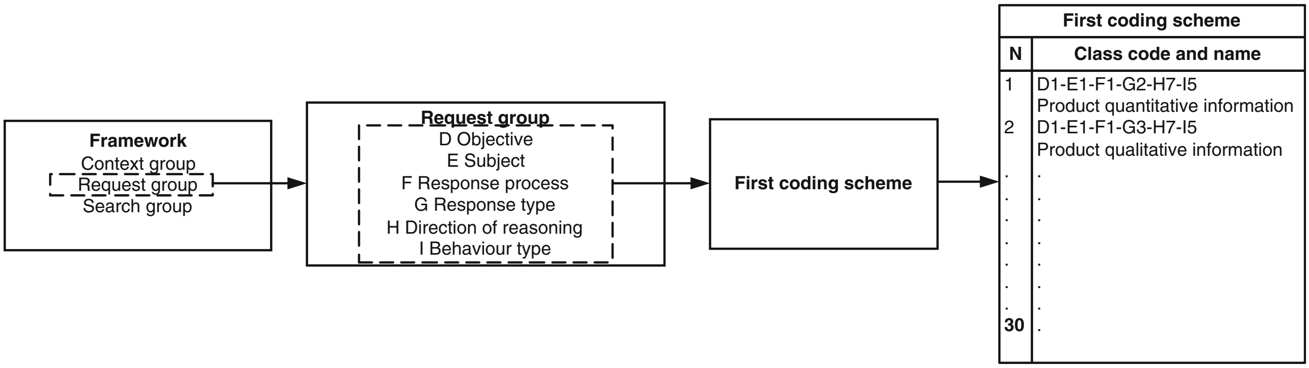


Fig. 3 From six categories to the first coding scheme

Table 16 First coding scheme

N	Class code and name			Description and example
1	D1-E1-F1-G2-H7-I5 Product quantitative information	Retrieval-recognition	Product	Find out product quantitative information by retrieval-recognition. Ex: *What is the diameter of the Trent 900 IPT production shaft?*
2	D1-E1-F1-G3-H7-I5 Product qualitative information			Find out product qualitative information by retrieval-recognition. Ex: *What material does the Trent 800 use for this part?*
3	D1-E1-F1-G5-H7-I5 Product configuration information			Find out product configuration information by retrieval-recognition. Ex: *Which nuts are used on this shaft?*
4	D2-E1-F1-G1-H7-I5 Product info confirmation			Confirm product information by retrieval-recognition. Ex: *Have you got any probe with a thin jacket around it?*
5	D3-E1-F1-G4-H7-I5 Product information comparison			Compare product information by retrieval-recognition. Ex: *What is the T and P difference between the Antle and Trent 500 for this seal position?*
6	D1-E2-F1-G2-H7-I5 Process quantitative information		Process	Find out process quantitative information by retrieval-recognition. Ex: *What are the mechanical properties of this material?*
7	D1-E2-F1-G4-H7-I5 Process mixed quantitative and qualitative information			Find out process mixed quantitative and qualitative information by retrieval-recognition. Ex: *What specifications exist defining swaging?*
8	D1-E2-F1-G7-H7-I5 Process source			Find out process source by retrieval-recognition. Ex: *Stress report for Trent 800 HPIP stubshaft*
9	D2-E2-F1-G1-H7-I5 Process information confirmation			Confirm process information by retrieval-recognition. Ex: *Is the weldability of crown max-c and jethete as good as the material database suggests?*
10	D3-E2-F1-G4-H7-I5 Process information comparison			Compare process information by retrieval-recognition. Ex: *What are the differences in inspection requirements between a class 01 and a class 02 forging?*
11	D4-E1-F2-G4-H2-I1 Product functional decomposition Gen	Reasoning	Product	Generate a requirement by reasoning from product IB to IB. Ex: *How is the Antle gearbox going to scavenge oil?*
12	D4-E1-F2-G2-H3-I1 Product dimension definition Gen			Generate a dimension by reasoning from product IB to F. Ex: *How much should the diameter of the shroud to the Trent 900 RDS be increased to scavenge oil adequately?*
13	D4-E1-F2-G5-H3-I1 Product functional configuration Gen			Generate a configuration by reasoning from product IB to F. Ex: *How can we flood the oil in the gearbox?*
14	D4-E1-F2-G6-H3-I1 Product functional layout Gen			Generate a spatial layout by reasoning from product IB to F. Ex: *Where could I bring the oil jet in to best feed the bearing cage?*
15	D4-E1-F2-G5-H4-I5 Product DfX configuration Gen			Generate a configuration by reasoning from product X to F. Ex: *How can I make this part easier to machine?*
16	D4-E1-F2-G4-H5-I1 Product function Gen			Generate a function by reasoning from F to IB. Ex: *What could I use this part for?*
17	D5-E1-F2-G5-H3-I1 Product functional configuration Gen			Generate an explanatory configuration by reasoning from product IB to F. Analysis and evaluation are also required. Ex: *How does oil scavenge from this side of the chamber?*
18	D5-E1-F2-G5-H3-I3 Product diagnosis Gen			Generate an explanatory cause to an UB by reasoning from product OB to F. Analysis and evaluation are also required. Ex: *What causes the oil leak?*
19	D5-E1-F2-G4-H5-I1 Product function Gen			Generate an explanatory function by reasoning from product F to IB. Analysis and evaluation are also required. Ex: *What is the function of the deviated feature?*
20	D6-E1-F2-G2-H5-I2 Product functional form Ana			Analyse by reasoning from product F to PB. Ex: *What is the impact on stress of increasing the OD of the shroud?*
21	D6-E1-F2-G4-H6-I5 Product DfX form Ana			Analyse by reasoning from product F to X. Ex: *What does this screen do to the cost of the pump?*
22	D6/D7-E1-F2-G1-H5-I2 Product functional form Ana/Eva			Analyse by reasoning from product F to PB. Evaluation is also required. Ex: *Can I make a feature like this to create a pocket and then be able to feed the external bearings?*
23	D6/D7-E1-F2-G1-H6-I5 Product DfX form Ana/Eva			Analyse by reasoning from product F to X. Evaluation is also required. Ex: *Will the bracket fit the wrong way round if assembled incorrectly?*
24	D7-E1-F2-G4-H2-I2/I1 Product functional form Eva			Evaluate by reasoning from PB to IB. Ex: *Is the stress in the HPIP hub acceptable?*
25	D4-E2-F2-G4-H7-I4 Process Gen		Process	Generate a process by reasoning (flow chart). Ex: *Where could I best start this task?*
26	D5-E2-F2-G4-H7-I4 Process Gen			Generate a process explanation by reasoning. Analysis and evaluation are also required. (flow chart). Ex: *How was the Trent 700 IP bolted joint signed off?*
27	D6/D7-E2-F2-G1-H7-I4 Process Ana/Eva			Analyse a process by reasoning. Evaluation is also required. (flow chart) Ex: *Is this process correct to calculate the balancing?*
28	D5-E1-F3-G4-H7-I5 Product rationale Gen	Deliberation	Product	Generate an explanatory rationale. Analysis and evaluation are also required. Ex: *Why have they gone for that design?*
29	D6-E1-F3-G4-H7-I5 Product Ana			Analyse the request subject/s by deliberation. Ex: *What is the impact of increasing the OD of the shroud?*
30	D6/D7-E1-F3-G1-H7-I5 Product Ana/Eva			Analyse the request subject/s by deliberation. Evaluation is also required. Ex: *Can we increase the outer diameter of the Trent 900 shroud tube?*

Despite the many *possible* combinations, the extraction of the scheme was not a challenging issue. In order to help explain this point, it is important to consider the way in which the categories were *designed* and the data were *classified*. Although the six categories apply to any information request, the *defined direction of reasoning* category was designed to characterise reasoning requests only. This means that many combinations *lacked meaning* and were, therefore, not considered. In addition, many combinations were considered *having meaning* but *not* being *possible*, due to the way the data were classified, see Appendix 2.

The first coding scheme includes 30 request classes identified through headings, examples and codes, see Table 16. It is noteworthy that the class codes are colour tagged to show groups of classes with the same root. The classes are presented divided into three sets following the types of the response process category, that is, retrieval-recognition, reasoning and deliberation.

The retrieval-recognition set (F1) includes 10 classes, see Table 16. These are all characterised by the ending (H7-I5), which means that the category defined direction of reasoning was not assigned a value. The classes from 1 to 5 are product-based (E1), while the classes from 6 to 10 are process-based (E2).

The reasoning set (F2) includes 17 classes, see Table 16. The classes from 11 to 24 are product-based (E1), while those from 25 to 27 are process-based (E2). Consider for example the classes from 11 to 16 and refer to the arc that each request type intends to complete in the graphs in Fig. 2. These indicate the objective to accomplish *constructive generation* (D4). In particular, class 11 (functional decomposition, arc 1) intends to generate a functional decomposition, whereas the classes from 12 to 14 (design, arc 1) to generate a design from a functional requirement, see Table 16. These requests differ in the nature of the design definition that they attempt to achieve, that is, numerical value (G2), configuration (G5) and layout (G6). Moreover, class 15 (design, arc 1) intends to generate a design from X and class 16 (function assignment, arc 1) to generate a new function to be performed using an existing form.

The deliberation set (F3) includes three classes, see Table 16. The classes from 28 to 30 are all product-based (E1) and characterised by the ending (H7-I5), which means that the category *defined direction of reasoning* was not assigned a value. This is because, although these requests indicate a high-level goal towards which the questioner is directed, it is not possible to infer what the questioner intends to focus on in order to answer them.

6.2 Discussion of first coding scheme

Previous classifications of information requests were found to include classes that either did not indicate an underlying structure or partly indicated the relationships between classes without an explicit model. This issue made it difficult to understand which characteristics of information requests the classes describe. The scheme proposed in this paper was extracted from six categories designed to describe distinct characteristics of information requests. With its 30 classes and a structure that draws upon a model of problem-solving, the scheme characterises in detail and unambiguously the information requests that designers are interested in.

Eris' classification includes four subgroups of classes termed, respectively, Other, Judgmental, Deep Reasoning Questions (DRQ) and Design Generative Questions (GDQ) (Eris 2002, 2004). The main contribution of Eris' work was the GDQ subgroup as the DRQ subgroup was previously identified by Graesser (Graesser and McMahen 1993). The Other subgroup is comparable to the retrieval-recognition set, whereas the DRQ and GDQ subgroups have similarities with the reasoning set. However, the DRQ and GDQ subgroups did not characterise the reasoning requests with the accuracy achieved in this research, for example reasoning requests were not distinguished by the problem type. Finally, in Eris' classification, there is no specific subgroup of questions mapping to the deliberation set. This indicates that information requests involving multiple inferences were not previously identified and are a novel set.

6.3 Reliability test

The coding scheme was tested for reliability using the Cohen's kappa coefficient as described in Bakeman and Gottman (1997). The researcher and two research students classified independently 30 requests. The two research students were not related to this project and from now on are referred to as coders. Prior to classifying the requests, the coders were provided with working definitions for each request class in the scheme. The requests that the coders were asked to classify were randomly selected from the data sets with the constraint that half of them had to be from the retrieval-recognition set and the other half from the reasoning and deliberation set. The classification produced by the two coders was compared to that of the researcher. The kappa coefficient was estimated to be 0.85 and 0.89, which indicated a high inter-coder reliability. The disagreements of the coder with a kappa coefficient of 0.85 were mainly related to requests that the researcher assigned to classes in the deliberation set. Differently, the disagreements of the coder with a kappa coefficient of 0.89 were equally related to requests that the researcher had assigned to the classes in the reasoning and deliberation sets.

6.4 Second coding scheme

The second coding scheme was extracted from the first three categories in the *request group*, see Fig. 4.

Using the same procedure described to extract the first scheme, it was found that the requests in the data sets could be classified around *17 request classes* instead of the 30 in the first coding scheme, that is, a reduction of 13 classes. The second coding scheme is composed of a *retrieval-recognition* set including 6 classes, a *reasoning* set including 8 and a *deliberation* set including 3, see Table 17.

6.5 Discussion of second coding scheme

The second coding scheme was developed to present the main quantitative *trends* in the data sets. The scheme, compared to the individual categories from which it was extracted, is a more accurate analytical tool.

The scheme differs from the first because it looses the detail provided by the *response type* and *defined direction of reasoning* categories. These categories were excluded because they were judged of secondary interest. Consider for example the request classes from 11 to 16 in the reasoning set of the first coding scheme, see Table 16. These classes are all characterised by the string (D4-E1-F2) and differ by the types in the remaining three categories. In the second coding scheme, these classes were merged in the request class 7 in Table 17. This class indicates that a request intends to accomplish constructive generation but does not characterise it by the *response type* and *defined direction of reasoning*. Hence, it is no longer possible to distinguish between generation to decompose a function, to design or to assign a function.

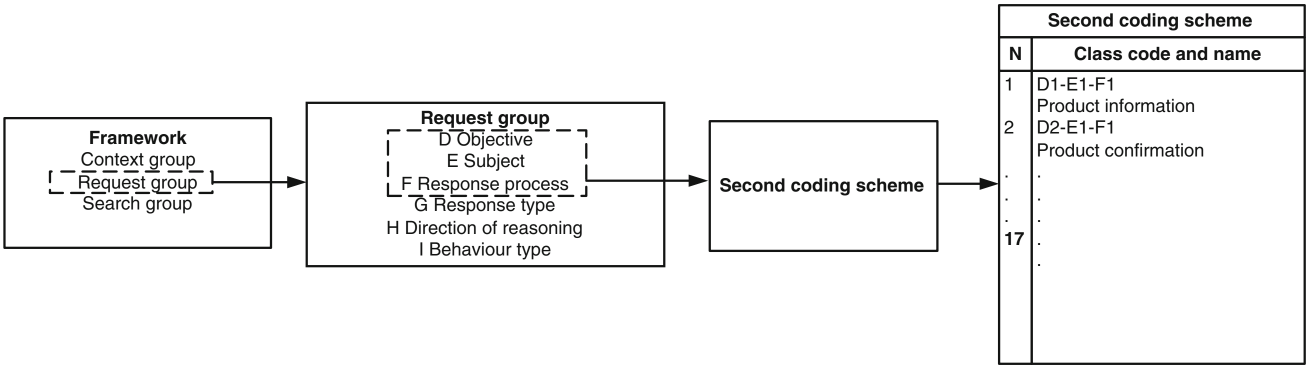


Fig. 4 From three categories to the second coding scheme

Table 17 Second coding scheme

N	Class code and name			Description and example
1	D1-E1-F1 Product information	Retrieval-recognition	Product	Ex: *What is the diameter of the Trent 900 IPT production shaft?*
2	D2-E1-F1 Product confirmation			Ex: *Have you got any probe with a thin jacket around it?*
3	D3-E1-F1 Product comparison			Ex: *What is the T and P difference between the Antle and Trent 500 for this seal position?*
4	D1-E2-F1 Process information		Process	Ex: *What are the mechanical properties of this material?*
5	D2-E2-F1 Process confirmation			Ex: *Is the weldability of crown max-c and jethete as good as the material database suggests?*
6	D3-E2-F1 Process comparison			Ex: *What are the differences in inspection requirements between a class 01 and a class 02 forging?*
7	D4-E1-F2 Product constructive Gen	Reasoning	Product	Ex: *How can we flood the oil in the gearbox?*
8	D5-E1-F2 Product explanatory Gen			Ex: *What causes the oil leak?*
9	D6-E1-F2 Product Ana			Ex: *What is the impact on stress of increasing the OD of the shroud?*
10	D6/D7-E1-F2 Product Ana/Eva			Ex: *Can I make a feature like this to create a pocket and then be able to feed external bearings?*
11	D7-E1-F2 Product Eva			Ex: *Is the stress in the HPIP hub acceptable?*
12	D4-E2-F2 Process constructive Gen		Process	Ex: *Where could I best start this task?*
13	D5-E2-F2 Process explanatory Gen			Ex: *How was the Trent 700 IP bolted joint signed off?*
14	D6/D7-E2-F2 Process Ana/Eva			Ex: *Is this process correct to calculate the balancing?*
15	D5-E1-F3 Product explanatory Gen	Deliber.	Product	Ex: *Why have they gone for that design?*
16	D6-E1-F3 Product Ana			Ex: *What is the impact of increasing the OD of the shroud?*
17	D6/D7-E1-F3 Product Ana/Eva			Ex: *Can we increase the outer diameter of the Trent 900 shroud tube?*

Table 18 Second coding scheme statistics

				Observations		
N	Code		Request class	C	%	CI
1	D1-E1-F1	Retrieval-rec.	Product information	33	13.7	± 4.3
2	D2-E1-F1		Product confirmation	22	9.1	± 3.6
3	D3-E1-F1		Product comparison	2	0.8	± 1.1
4	D1-E2-F1		Process information	34	14.2	± 4.4
5	D2-E2-F1		Process confirmation	28	11.6	± 4.0
6	D3-E2-F1		Process comparison	0	0.0	± 0.0
7	D4-E1-F2	Reasoning	Product constructive Gen	26	10.8	± 3.9
8	D5-E1-F2		Product explanatory Gen	7	2.9	± 2.1
9	D6-E1-F2		Product Ana	9	3.7	± 2.4
10	D6/D7-E1-F2		Product Ana/Eva	15	6.2	± 3.1
11	D7-E1-F2		Product Eva	3	1.2	± 1.4
12	D4-E2-F2		Process constructive Gen	0	0.0	± 0.0
13	D5-E2-F2		Process explanatory Gen	11	4.6	± 2.6
14	D6/D7-E2-F2		Process Ana/Eva	5	2.1	± 1.8
15	D5-E1-F3	Delib.	Product explanatory Gen	7	2.9	± 2.1
16	D6-E1-F3		Product Ana	2	0.8	± 1.1
17	D6/D7-E1-F3		Product Ana/Eva	37	15.4	± 4.6
				241	100.0	

C count; % per cent of total; *CI* confidence interval at 95 %

7 Analysis of the data sets using the second coding scheme

The distribution of the requests in the 17 classes of the second scheme is presented in Table 18.

The retrieval-recognition set shows that the request classes more frequently formed were *product information* (class 1) and *process information* (class 4) together with *product confirmation* (class 2) and *process confirmation* (class 5), see Table 18. The requests to obtain and confirm information operate at a low level of problem-solving. These requests are formed to satisfy rudimentary needs and to confirm information to support thinking when designing. The engineering designers in the collaborating company were observed working on interdependent tasks that often required confirming the occurrence of events and the truth of facts. In current manufacturing organisations, the answers to these requests are often available either through human or documentary sources.

The reasoning set shows that the frequency of the request class *product constructive generation* (class 7) was nearly double that of *product analysis/evaluation* (class 10) and more than double that of *process explanatory generation* (class 13). It is now worth remembering the characteristics of these three types. Product constructive generation requests were developed to define quantitative features, configurations and spatial layouts by reasoning from intended behaviour to form. Product analysis/evaluation requests were formed to analyse designs by reasoning from form to predicted behaviour or any other driver in the design process, for example cost. Process explanatory generation requests were raised to explain the process adopted by other designers in previous tasks. This result indicates that designers search externally to satisfy requests to define designs, to predict their performance and to learn from previously adopted processes. It is worth noting that the third type of request can be answered from a documentary source or a designer if the information is available, whereas the first and the second type require development of new information.

The deliberation set shows that the request class *product analysis/evaluation* (class 17) was formed at a significantly higher rate than the other request classes. These requests intended to analyse and evaluate designs and the questioners were looking for support to identify the issues relevant to the subject of the deliberation and to form the requests necessary to develop a view. These are again requests necessitating the development of new information and for which the consultation of an expert seems the only option to answer them.

8 Discussion

The requests studied in this research were collected from engineers working on variant design tasks to develop transmissions and structures for aerospace gas turbines. The participants were part of a department staffed with forty engineers, where multiple design projects are simultaneously undertaken. The research found that they raised an average of 2.5 requests per hour that made them search through external sources. This result is in line with previous research in the same organisation, which showed that the average occurrence of queries per engineer is 2.3 per hour (Marsh 1997). From this finding, it emerges clearly that pulling information is a key component of the design work undertaken by these professionals.

To understand what types of information the engineers attempted to pull, their requests were analysed through six categories and two coding schemes. The results have provided rich understanding of their information needs and engineering work. Firstly, the research found that 82 % of the requests intended to source current project information and 18 % to obtain information about another project or project independent. This result is significantly different from previous studies, which reported that approximately 50 % of requests is about new information and the other 50 % is about old information (Kuffner and Ullman 1991; Vijaykumar and Chakrabarti 2008). In these studies, it is possible that the lack of familiarly of the subjects with the design domain of the tasks studied increased the number of requests about old information (Kuffner and Ullman 1991; Vijaykumar and Chakrabarti 2008).

Analysing the data from the observations, it emerged that half of the requests were formed to *acquire information* and the other half to *process information*. The former were raised to support design thinking by satisfying basic information needs. The latter, instead, were raised to progress design thinking by reasoning and deliberation about problems and solutions. The conceptual distinction between these two types is in agreement with previous research in which the requests to *acquire information* were termed ‘questions about facts and attributes’ (Eris 2004) or ‘information transactions’ (Wasiak et al. 2010), while the requests to *process information* were referred to as ‘questions about generative design and deep reasoning’ (Eris 2004) or ‘problems solving behaviours’ (Wasiak et al. 2010).

Examining closely the requests to process information, three main subsets were identified as follows: product reasoning requests, product deliberation requests, and process reasoning requests.

Product reasoning requests were characterised in detail to explain their roles in the design process. During the exploration of past designs, these requests were used to make sense of structures, components and features as well as to understand their engineering functions supporting observations by Ahmed et al. (2003). If information about product structure can be easily accessed from CAD systems, functional information often cannot be easily sourced from documentary repositories. As a result, engineers tended to infer it from structural descriptions or to question their colleagues.

In early design work, product reasoning requests were raised to define and decompose engineering requirements. Differently, in the context of solution development, they were used to generate new features, configurations and spatial layouts as well as to analyse and evaluate them. The requests to generate solutions required divergent-thinking and the creation of possibilities, whereas those to analyse and evaluate solutions required convergent-thinking and the establishment of facts (Eris 2004). According to the design model proposed in C–K theory, the requests to generate new solutions can be seen as operating in the concept space, whereas the requests to analyse and evaluate solutions in the knowledge space (Hatchuel and Weil 2009). In particular, it was discussed that these requests cannot be answered through documentary sources. Therefore, the engineers had no alternative to posing them to their colleagues emphasising the importance of informal social interactions in solution development (Bucciarelli 1984, 1998).

In the context of engine development, product reasoning requests were raised to identify the causes of reported problems. Depending on the problem, the answers to these requests were either known information potentially accessible from documentary sources or new information.

Product deliberation requests were found to be compound. During solution development, these requests were predominantly used to analyse and evaluate proposed design solutions and make decisions upon them. Answering these requests involved convergent-thinking but it also required identifying relevant design issues and networks of dependent information requests. It can be argued that in this case, the engineers were looking for directions of investigation rather than definitive answers supporting the view of design as an inquiry process (Eris 2004). Similarly to the product reasoning requests to develop new solutions, deliberation requests had no alternative to being posed to other engineers.

Process reasoning requests, in the majority of the cases, required the engineers to understand the steps adopted in pervious tasks. The answers to these requests can be seen as sequences of actions needed to accomplish design work and were rarely accessible from documentary information.

Overall, the results suggest that the information requests sourced externally are an important route through which design unfolds together with individual design work and pre-scheduled team interactions.

8.1 Limitations and further work

The results of this research are based on the data sets of information requests gathered during summer 2002 and 2003 using a diary study and observations with shadowing. Although the data sets are approximately 10 years old, they are still current as they consist of information needs raised by engineers to design technical systems. It is plausible that today the subject of these information needs may have slightly changed due to engine technology development but not the other structural characteristics used to differentiate them. A limitation of the research is that only the observations provided data suitable to characterise with accuracy the information types that the engineers involved in this research attempted to pull. The data set from the diary study was found to have a bias towards specific information types and therefore considered unreliable. Another limitation is that all the information requests were collected from designers undertaking variant design tasks in a single department in a large aerospace company. To generalise the results, it would be necessary to research information requests formed as part of original and adaptive design tasks. In addition, more research would be needed in other departments within the collaborating company, in other aerospace companies, and in businesses operating in other engineering design domains.

The data set from the observations was aggregated from fifteen engineering designers working on design tasks belonging to different stages of the product development process. More research could be undertaken to investigate variations in the types of request formed across design stages. Further work is also needed to explain compound information requests such as those answered by deliberation.

The validity of the categories and the coding schemes need to be confirmed by applying them to other data sets of information requests. Finally, the research could be extended to investigate the requests formed during individual design activity that are answered internally, and the requests formed during group design activity. These investigations would provide the research community with a more comprehensive understanding of information acquisition and processing.

8.2 Practical and theoretical implications

Based on the result that half of the requests were to acquire design and domain information, a strategy to support engineers should investigate opportunities to improve the performance of data management systems (PLM, CAD, CFD, FEA), databases (standards and materials) and search engines. Tools for computer supported cooperative work (CSCW) could be useful to enable real-time sharing of newly generated information between engineers working on interdependent tasks. However, the main message is that implementing information codification approaches is not sufficient on its own (McMahon et al. 2004). In fact, the other half of the requests formed by the engineers were to process information. These required the engineers to make inferences about existing designs and synthesise new information that cannot be found in documentary sources. Data management systems (PLM, CAD, CFD, FEA) can be used to better support the requests about existing designs. There is, however, a need to actively promote personal interactions and foster engineering communities that can efficiently share, integrate and co-create knowledge (Kleinsmann et al. 2012). A complementary solution to promoting communities of practice is to provide engineers with software tools to ask the right questions (Wang and Zeng 2009) and to map design inquiries focusing on design questions, answers and argumentation (Bracewell et al. 2009).

This work advances our understanding of information requests by characterising new types and explaining how they are used in the design process by engineering designers in industry. More so, the research provides a methodology to deconstruct and characterise information requests at a very fine-grained level. The framework, the six request categories and the coding schemes could be instruments of value for analysis of requests gathered from design domains other than aerospace engineering. Finally, this work contributes to research in this area by showing how to employ a rigorous and systematic approach to analysis and codification of design information, which was only possible because of the understanding developed through research in industry.

9 Conclusions

This research found that current classifications of information requests are incomplete and argued that more research in this area is needed to improve the support that can be provided to engineering designers. The research produced additional evidence that a process view is more adequate than an information centric view to describe the requests made by designers upon information. The results showed that approximately half of the requests with which designers approach external sources are to *acquire information* and the other half to *process information*. The requests to process information were formed to revisit existing designs as well as to develop new solutions and were instrumental in enabling the progression of design work. More so, they were answered through complex response processes like reasoning and deliberation and were found to operate at a higher level of design thinking than the requests to acquire information. In developing this understanding, the observations with shadowing, not surprisingly, provided richer data and a greater number of insights than the diaries. The employment of an ethnographic study in the early stages of the research provided important understanding of information requests and informed research methodology development and data analysis. The use of three types of study enabled the data to be triangulated and thus increased the objectivity of the overall results.

The research demonstrated that six categories and the schemes extracted from them enabled information requests to be characterised in a way that differs in structure and descriptiveness from contributions gained in previous projects. Each scheme provides a more comprehensive view on information requests than relying just on a single category. The method used to classify information requests proved to be very flexible as it allowed the development and updating of the categories as the analysis of the data progressed.

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Appendix 1

Tables 19 and 20 present the results of the pair-wise Kendal correlation test on the data sets from the diary study and the observations.

Appendix 2

The way the data were classified in the *objective* (D) and *response process* (F) categories deserves special note. The requests without an objective and with low-level objectives (from D1 to D3) were *always* answered employing retrieval-recognition and therefore classified as such. Differently, the requests with high-level objectives (from D4 to D7) were answered employing one of the three response processes depending on the nature of the problems being addressed, the selected source and the interaction between the questioner and the source. 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.

Table 19 Kendal correlation test

Diary study	E	F	G	H–I
D	−0.26	0.84	−0.35	0.48
E		−0.29	0.40	0.06
F			−0.24	0.47
G				0.09

Table 20 Kendal correlation test

Observations	E	F	G	H–I
D	−0.33	0.80	−0.30	0.45
E		−0.42	0.15	−0.08
F			−0.10	0.34
G				0.21

References

Ahmed S, Wallace KM, Blessing LTM (2003) Understanding the differences between how novices and experienced designers approach design tasks. Res Eng Design 14:1–11

Aurisicchio M (2005) Characterising information acquisition in engineering design, PhD Thesis, Engineering Department, Cambridge University

Aurisicchio M, Bracewell R, Wallace K (2010) Understanding how the information requests of aerospace engineering designers influence information-seeking behaviour. J Eng Des 21(6):707–730

Bakeman R, Gottman JM (1997) Observing interaction—an introduction to sequential analysis, Cambridge University Press, Cambridge

Baya V (1996) Information handling behaviour of designers during conceptual design: three experiments, PhD thesis, Department of Mechanical Engineering, Stanford University

Blessing LTM, Chakrabarti A (2009) DRM, a design research methodology, Springer, New York

Bracewell RH, Sharpe JEE (1996) Functional descriptions used in computer support for qualitative scheme generation—"Schemebuilder". AI EDAM J 10:333–346

Bracewell RH, Wallace KM, Moss M, Knott D (2009) Capturing design rationale. Comput Aided Des 41:173–186

Bucciarelli LL (1984) Reflective practice in engineering design. Des Stud 5(3):185–189

Bucciarelli LL (1998) An ethnographic perspective on engineering design. Des Stud 9:159–168

Court AW (1995) The modelling and classification of information for engineering designers, PhD thesis, University of Bath

Coyne R (1988) Logic models of design. Pitman, London

DeLongis A, Hemphill K, Lehman D (1992) A structured diary methodology for the study of daily events, methodological issues in applied psychology. Plenum Press, New York, pp 83–109

Dorst K, Hendriks D (2001) The role of the design context: in practice and in design methodology. In: Lloyd P, Christiaans H (eds) Designing in context, 18–20 December. Delft University Press, Delft, The Netherlands

Ericsson KA, Simon HA (1993) Protocol analysis: verbal reports as data. MIT Press, Cambridge, MA

Eris O (2002) Perceiving, comprehending, and measuring design activity through the questions asked while designing, PhD Thesis, Department of Mechanical Engineering, Stanford University

Eris, O (2004) Effective inquiry for innovative engineering design. Kluwer Academic Publishers, Boston

Gero JS (1990) Design prototypes: a knowledge representation schema for design. AI Mag 11(4):26–36

Gero JS, Kannengiesser U (2004) The situated function-behaviour-structure framework. Des Stud 25(4):373–391

Graesser A, McMahen C (1993) Anomalous information triggers questions when adults solve quantitative problems and comprehend stories. J Educ Psychol 85(1):136–151

Gruber TR, Russell DM (1992) Derivation and use of design rationale information as expressed by designers. KSL 92–64, Stanford, CA

Gruber TR, Russell DM (1996) Generative design rationale: beyond the record and replay paradigm. In: Moran T, Carroll J (eds) Design rationale: concepts, techniques, and use, Lawrence Erlbaum Associates. Hillsdale, USA, pp 323–349

Hatchuel A, Weil B (2009) C-K design theory: an advanced formulation. Res Eng Design 19:181–192

Heisig P, Caldwell NHM, Grebici K, Clarkson PJ (2010) Exploring knowledge and information needs in engineering from the past and the future—results from a survey. Des Stud 31:499–532

Kleinsmann M, Deken F, Dong A, Lauche K (2012) Development of design collaboration skills. J Eng Des 23(7):485–506

Kroes, PA (1998) Technological explanations: the relation between structure and function of technological objects. J Soc Philos Technol 3(3):18–34

Kuffner TA, Ullman DG (1991) The information request of mechanical design engineers. Des Stud 12(1):42–50

Langdon P, Aurisicchio M, Clarkson PJ, Wallace KM (2003) An integrated ethnographic and empirical methodology in a study of knowledge searches in aerospace design, in 14th international conference on engineering design. Stockholm, Sweden

Lehnert GW (1978) The process of question answering. Lawrence Erlbaum Associates, Hillsdale, New Jersey

MacGregor SP, Thomson AI, Juster NP (2001) A case study on distributed, collaborative design: investigating communication and information flows. Sixth international conference on computer supported collaborative work in design, London, ON, Canada, pp 249–254

March L (1984) The logic of design. In: Cross N (ed) Developments in design methodology. Wiley, Chichester, pp 265–276

Marsh JR (1997) The capture and utilisation of experience in engineering design, PhD Thesis, Engineering Department, Cambridge University

McMahon C, Lowe A, Culley S, Corderoy M, Crossland R, Shah T, Stewart D (2004a) Waypoint: an integrated search and retrieval system for engineering documents. J Comput Inf Sci Eng 4(4):329–338

McMahon C, Lowe A, Culley SJ (2004b) Knowledge management in engineering design, personalisation and codification. J Eng Des 15(4):307–325

Moore C (1997) Design technology for the aero engine. In: Proceedings, 11th international conference on engineering design, Tampere

Patel VL, Ramoni MF (1997) Cognitive models of directional inference in expert medical reasoning. In: Feltovich PJ, Ford KM, Hoffman RR (eds) Expertise in context—human and machine. The MIT Press, Menlo Park, CA, pp 67–99

Ranganathan SR (1963) Colon classification: basic classification. Asia Publishing, Bombay

Robinson M (2010) An empirical analysis of engineers' information behaviours. J Am Soc Sci Technol 61(4):640–658

Roozenburg NFM (1993) On the pattern of reasoning in innovative design. Des Stud 14(1):4–18

Roozenburg NFM, Eekels J (1995) Product design: fundamentals and methods. Wiley, Chichester

Tomiyama T, Takeda H, Sasaki H, Yoshioka M, Shimomura Y (2003) Abduction for creative design. In: Liption H, Antonsonn EK, Koza JR (eds) Working notes for AAAI-2003 spring symposium series on computational synthesis: from basic building blocks to high level functionality

Ullman DG (1988) A model of the mechanical design process based on empirical data, AI EDAM

Vijaykumar G, Chakrabarti A (2008) Understanding the knowledge needs of designers during design process in industry. ASME J Comput Inf Sci Eng 8:1

Waldron MB, Waldron KJ, Abdelhamied K (1987) The differences in reading schematic drawings of mechanisms by expert and naive mechanical designers, in ICED, pp 15–21

Walton DN, Krabbe ECW (1995) Commitment in dialogue: basic concepts of interpersonal reasoning. State University of New York Press, Albany, NY

Wang M, Zeng Y (2009) Asking the right questions to elicit product requirements. Int J Comput Integr Manuf 22(4):283–298

Wasiak J, Hicks B, Newnes L, Dong A, Burrow L (2010) Understanding engineering email: the development of a taxonomy for identifying and classifying engineering work. Res Eng Design 21:43–64

Wild PJ, McMahon C, Darlington M, Liu S, Culley S (2010) A diary study of information needs and document usage in the engineering domain. Des Stud 31(1):46–73