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Understanding the Knowledge Needs of Designers During Design Process in Industry

Product success is substantially influenced by satisfaction of knowledge needs of designers, and many tools and methods have been proposed to support these needs. However, adoption of these methods in industry is minimal. This may be due to an inadequate understanding of the knowledge needs of designers in industry. This research attempts to develop a better understanding of these needs by undertaking descriptive studies in an industry. We propose a taxonomy of knowledge, and evaluate this by analyzing the questions asked by the designers involved in the study during their interactions. Using the taxonomy, we converted the questions asked into a generic form. The generic questions provide an understanding about what knowledge must be captured during design, and what its structure should be. [DOI: 10.1115/1.2840776]

1 Introduction

In a globalizing world, companies face stringent requirements for innovation, with reduced cost, high quality, and less time to develop products. Industry needs to satisfy these requirements in spite of the high attrition rate of product development personnel. To compete in the current scenario, companies must enhance reuse of internal and external knowledge, concentrate on core competence by making maximal use of components and services available on the world market, form virtual enterprise with firms focusing on complementary core competence, and change its culture by replacing previous competition by new forms of cooperation.

To retain core competence, organization must capture, structure, and make available for reuse across projects the knowledge developed in design. 70–95% of design work could consist of reusing, configuring, and assembling of existing components, solutions, and knowledge [1]. Capturing necessary knowledge developed in design aids in (re)design of similar products, communication between designers and others, understanding design, explanation of the design process, training of novices, and avoidance of "reinventing the wheel."

Many knowledge reuse approaches, representations, and capture and retrieval methods are proposed in literature. However, adoption of these in industry is minimal. One reason could be that the knowledge needs of designers are not appropriately understood and addressed. This research attempts to bridge this gap by undertaking descriptive studies in an industry in order to understand the knowledge needs of its designers during design.

The paper is organized into eight sections. Section 2 surveys literature on knowledge processing and establishes the relevance of this paper. Section 3 elaborates a model of relations among knowledge and frames a set of research questions. Section 4 discusses the methods employed to collect data from industry and their limitations. Section 5 proposes a taxonomy of knowledge. Section 6 analyzes the questions asked by designers during their interactions. Section 7 uses the taxonomy to frame generic questions from designer questions. Sections 8 and 9 provide discussion, conclusions, and future work.

2 Literature Survey

In this section, we establish the need to understand knowledge processing activities and the kinds of knowledge representation necessary.

2.1 Need to Understand Knowledge Processing Activities. In Ref. [2] it was argued that availability of information is central for design success. Marsh [3] observes that designers spend on average 24% of their time in information acquisition and dissemination; majority of this information is obtained from personal contacts rather than formal sources. Project delays are mainly due to time spent in information access and acquisition; delays range from a single day to a year [4]. Engineers use company systems and colleagues in the same office to get information, and perceive that 34% of their time is taken in sourcing and locating relevant information [5]. Ottosson [6] estimates that less than 20% of the information acquired is used in building up new pictures of the world; the rest comes from earlier pictures stored in the brain. Busby [7] found that engineers often failed to learn from their experiences because feedbacks provided to them from previous projects were often unreliable, delayed, negative, or missing. Stewart [8] argues that currently only 20% of a firm's knowledge is effectively used.

From these, we conclude that availability of information and knowledge influences designing in terms of the time spent and quality of its outcomes. Current documents are not preferred by designers due to the time involved in getting the right information and characteristics of the content (accuracy and recency). A firm's knowledge would be effectively utilized if knowledge generated in its different projects are captured, structured, and reused across projects. To do so, an effective representation schema to structure the captured knowledge is required.

2.2 Benefits of Knowledge Representation. The usefulness of the information captured in a design history depends on how it is indexed. Documentation and design process information must be well organized to facilitate automatic processing and search operations [9]. The cost of interoperability barriers among IT systems used in engineering and manufacturing in the US autoindustry is estimated to be about $1 billion per year [10]. Good knowledge representation schema should help solve interoperability issues. Development of standards for knowledge representation is one of the mechanisms by which knowledge sharing and reuse might be achieved [11]. Having appropriate knowledge representation schema could make knowledge capture and reuse efficient.

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2.3 What Is Knowledge Representation? The answer to this question is best given in Ref. [12], which argues that knowledge representation can be understood as a

1. surrogate, a substitute for the thing itself, used to enable an entity to determine consequences by thinking rather than acting, i.e., by reasoning about the world rather than taking action in it
2. set of ontological commitments, i.e., an answer to the question: In what terms should I think about the world?
3. fragmentary theory of intelligent reasoning, expressed in terms of (i) the representation's fundamental conception of intelligent reasoning, (ii) the set of inferences the representation sanctions, and (iii) the set of inferences it recommends
4. medium for pragmatically efficient computation, i.e., a computational environment in which thinking is accomplished. One contribution to this pragmatic efficiency is supplied by the guidance a representation provides for organizing information so as to facilitate making the recommended inferences
5. medium of human expression, i.e., a language in which we say things about the world

Even though all the points mentioned above are relevant in the current scenario, a knowledge representation should primarily address these to surrogate the domain of interest unambiguously, aid selection of appropriate representations, and aid communication with ease (Points 1, 2, and 5). This paper focuses on these issues.

2.4 Kinds of Knowledge Representation. This section discusses the current approaches, models, and representations relevant for this paper.

2.4.1 Approaches. The differences between knowledge management generations, i.e., the distinction between a commodity view or codification strategy or feature-oriented approach (standardized products) and a community view or personalization strategy or process-oriented approach (customized solutions), are illustrated in Refs. [13–15]. Process-oriented approaches help designers by providing descriptive history information to answer questions, e.g., what decisions are made, when, by whom, and why. These approaches record the history of design activities, work flow, and communication between designers. The representations, e.g., issue based information system (IBIS), decision rationale language (DRL), and procedural hierarchy of issues (PHI), are based on this approach.

Feature-oriented approaches collect and organize domain knowledge and consider knowledge in discrete units to represent the design space of an artifact. These approaches are more applicable during detail design stages, whereas process-oriented approaches are more applicable in conceptual stages [16]. Each approach has limitations in representing knowledge to be captured for reuse during design. These complimentary approaches must be linked together to increase the expressiveness of knowledge representation schema, helping understand both the logical structure of the artifact being designed and the history of design.

Venselaar et al. [17] typify knowledge into domain-specific and general knowledge, with each type classified further into four subtypes (declarative, procedural, situational, and strategic knowledge). In this classification, declarative knowledge would be under feature-oriented approach, whereas procedural, situational, and strategic knowledge would be under process-oriented approach. The subsequent subsections discuss existing knowledge representations.

2.4.1.1 Process-Oriented Approach. The classifications of knowledge covered under process-oriented approaches are discussed in this section. Knowledge generated by projects is classified in Ref. [18] as knowledge in projects, knowledge about projects, and knowledge from projects. A descriptive model [19] uses conjectures, criteria, and interactions between them to enable capture of design process rationale. While conjectures capture alternatives, criteria provide access to rationale behind the alternatives. The foremost representation in process-based approaches is IBIS [20]. It consists of three categories (issue, proposal, and argument) and eight types of relationships among them. The other representations are PHI [21], question, option, and criteria (QOC) [22], and design rationale authoring and retrieval system (DRARS) [23]. These classifications are designed to capture deliberations occurring during design. The intention is to support the transition from expression to documentation, from informal, incomplete, private rationale to more formal, complete, and publicly intelligible rationale.

Kruger [24] describes analysis in conceptual design by the following activities: select information, verify information, identify relevant facts, explicit and implicit constraints, establish a working model, and define requirements. References [25,26] are other notable contributions for classifying designers' activities. The representation proposed in Ref. [25] consists of predefined categories in the form of matrices to capture generation, evaluation, and selection processes in design. Designers' activities in Ref. [26] are categorized under problem understanding (identify, analyze, choose) and problem solving (generate, evaluate, select). In these approaches, activities of designers are explained, but product-related knowledge is not considered.

2.4.1.2 Feature-Oriented Approach. A number of representations are proposed to characterize the artifact being designed and information requests of designers; some are discussed here. In Ref. [27], design history is defined as a representation of the evolution of a product from its initial specifications. It is argued that in order to develop a usable design history, the types of information needed by designers when they attempt to understand a design must be determined. Their taxonomy of questions asked by designers consists of category, topic, age of topic, nature, confirmation, and validity. Significant findings were 51% of the questions and conjectures were about old topics, and a high percentage of questions and conjectures was about the construction of features and components. In Ref. [28], it was shown that, for generating new product concepts using information from previous design effort, designers used both conceptual and detail level information almost in equal proportions. Also, the number of queries in product construction and description accounted for almost half of the queries, and the subject-class *component level* received 43% of the queries.

Gruber and Russell [29,30] propose an approach for acquiring justifications by transforming why questions into what questions. They transformed extracted segments of protocols into generic questions using a limited vocabulary of abstract terminology. Analyzing all the protocols collected, they produced a set of 63 generic questions. Each question represents a kind of information need or use, and a potential opportunity for computational support. For each generic question, there are one or more generic answers. They summarized the range of generic answers by grouping them by the *format* of the answer. Their categories are based on the information requests of designers primarily considering the designed artifact.

In Ref. [31], product knowledge is represented as requirements, specifications, artifact (subartifacts, functions, form, and behaviors), design rationale, constraints, and relationships. Another approach [32] is based on an extension of the function-means tree model of design and on the chromosome model for product modeling to concurrently document the design history. The extended function-means tree model includes functional requirement, means, objective, and constraint objects, and solved by, alterative solutions, and requirements on, and has influence on relations.

Notable representations characterizing an artifact are functional representation (FR) [33], structure, behavior, and function (SBF) [34], and purpose, function, behavior, and structure [35]. In Ref. [36], a technical system and the transformation process it creates are described in terms of process, function, organ, and component structures. In Ref. [37], it is argued that design specifications and structures are linked by causal relations: The process determines the functions, which are created by the organs, which are materialized by the components. In Ref. [38], SAPPhIRE model following constructs are proposed: state, action, part, phenomenon, input, organ, effect, and their relationships. These models consider product-related knowledge but not process-related knowledge.

Combination of approaches. This section discusses the representations that combine feature-oriented and process-oriented approaches. The representations where *design artifact* related terms are included into a predominantly process-based approach are Potts and Bruns method [39], DRL [40], object-relation-object (OREO) [41], and representation and maintenance of process knowledge (REMAP) [42]. Aurisicchio [43] investigates the nature of requests formed by designers during design and their associated searches. The categories considered in the request group are objective, subject, response process, response type, directions of reasoning, and behavior type. The main findings are as follows: In the total number of requests recorded, the percentages of retrieval recognition, reasoning, and deliberation were 50%, 30%, and 20% respectively, and 70% of the requests were sourced through interactions with colleagues.

In Ref. [44], a design reuse model is proposed which consists of processes for design by reuse, domain exploration, and design for reuse, and six knowledge-related components: design requirements, sources of domain knowledge, reuse library, domain model, evolved design model, and completed design model. Smith and Duffy [45] argue that knowledge from the earlier stages of design (function, behavior, solution concepts) and the *how* and *why* (rationale) of a designed artifact are key elements to the reuse approach. Taura and Kubota [46] build an "engineering history base," from which engineers can retrieve explanations to enable reuse of product information. They argue that explanation from the "process" viewpoint is important in promoting reuse of product information. Process information is modeled using a process unit comprised of five elements: action, object, alternative, constraint, and reason. Product information is modeled using product class, data file class, and attribute class.

KBDS, a prototype support system for conceptual design of chemical processes based on an IBIS representation to record design rationale, is extended in Ref. [47], arguing that this integration extends our capability to represent the design process and account for design decisions, alternatives, models, constraints, specifications, and justifications in an integrated and prescriptive form. In Ref. [48], a parameter dependency network is used to represent design rationale. The network shows how a particular design decision affects other decisions that affect further decisions. Both domain-dependent knowledge and domain-independent rationale storage module are considered. The *depends-on* and *has-relationship* semantic net links generate the parameter dependency network.

2.5 Challenges in Knowledge Representation. Though simple approaches to reuse can be taken, it is argued in Ref. [49] that the volume of data involved and the complexity of interaction of relationships implicit in data lead to the need for supporting methodologies, techniques, and tools. Ullman [50] argues that design reuse process model should consider reuse as a total process, which can encompass all phases of the design life cycle. Common solutions for migration and retrieval of information are simply overtaxed because of the lack of semantics [51]. They suggest the use of ontology technology as the key to overcome the shortcomings by means of enabling network-wide information management at higher semantic levels. The barriers impeding realization of the overall concept of knowledge reuse and sharing [52] are the following.

- Various knowledge representation schemes can be adopted in developing a knowledge base.
- Within a single knowledge representation scheme, various implementation dialects could be used.
- Shared sets of explicitly defined terminology for describing and structuring knowledge are lacking.

These points are still applicable to the current research on knowledge representation. It is necessary to develop representations that should enhance the expressiveness through understanding of semantics and covering the entire product life cycle.

2.6 Summary of Literature Survey. On average, designers spend 30% of their working time in knowledge acquisition and dissemination. The efficacy of designers will be improved significantly if knowledge generated during the design process is appropriately organized for reuse. Only some knowledge representation schemes are based on understanding the knowledge needs of designers. Others attempt only to map the design space. Note that most descriptive schemes were proposed from data collected under laboratory settings. Knowledge needs of designers in industry are yet to be comprehensively observed and identified, particularly across different stages of the design process. The key element influencing the expressiveness of a representation is the integration of feature-oriented and process-oriented approaches. The representations of argumentation, designer's activities, and the artifact being designed must be linked together considering the knowledge needs of designers. Even though part of the representations falls in combination of approaches, the linkages between them are not clear. The subsequent sections address some of the gaps found in literature.

3 Model of Relations Among Knowledge and Research Questions

In order to understand the knowledge reuse spectrum (see Fig. 1), it is necessary to study the knowledge produced, captured, and reused during the design process.

The following research questions are formulated.

- What knowledge is produced during design process?
- What portion of it is currently captured?
- What portion of it is currently reused?
- What knowledge is developed but not captured that should be otherwise?

The focus of this paper is to address only the last question—what knowledge is developed but not captured that should be otherwise. To answer this, we must understand the knowledge needs of designers and knowledge captured currently during the design process. To do so, we analyzed the questions asked by the designers in an industry in various interactions, and observed the knowledge captured during their design process. The data collection methods are described in the next section.

4 Data Capture Methods and Limitations

To answer the research questions, a series of industrial case studies were undertaken. Three designers involved in different projects were observed serially for 5 days, 3 days, and 7 days, respectively. Initial plan for observation was to observe three designers for 5 days each. The observation of the second designer was stopped on the fourth day because of his unavailability due to personal grounds. This is one of the limitations of case studies in industry that researcher has little control over the proceedings. In this paper, we analyzed entire set of data collected from the observed interactions of these three subjects with other colleagues. Though we focused only on three designers, the data include the knowledge needs of the other eight designers who interacted with the three designers under focus. The average times observed per day for the three subjects were 5.4 h, 3 h, and 2.8 h, respectively. The observed durations do not include time spent by the subjects for personal activities. The difference in the observed durations

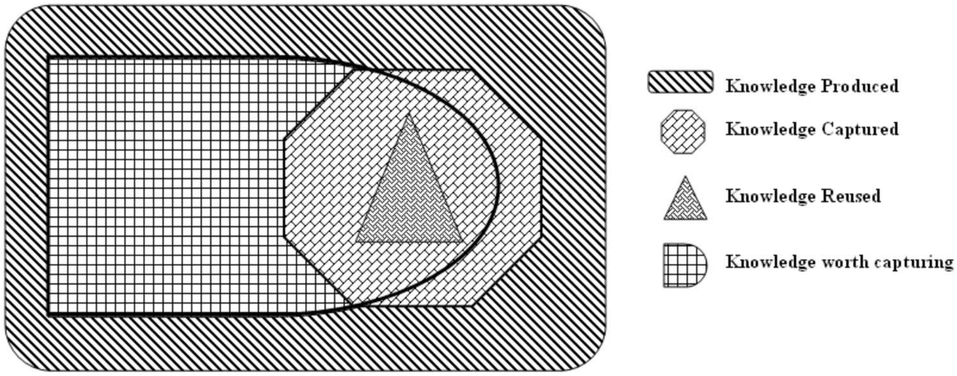

Fig. 1 A model of relations among knowledge

among subjects was due to the limitations of observation, e.g., interactions occurring outside the organization and the mode of working of the observed designers. Table 1 details the tasks performed by the designers during the observed periods, the respective design stages, and the number of questions captured in each task (mentioned in the parentheses). To ensure confidentiality of information collected from the industry, the tasks are represented generically. All tasks observed are original tasks, i.e., done for the first time by the designers.

The data collection methods used are questionnaires, unstructured interviews, voice recordings, digital snapshots, video recordings, desktop sharing, and data sheets. To answer the question under focus in this paper, data sheets, audio recording, questionnaires, and interviews were used. Data sheets gave details about the purpose of the tasks, interactions, place of interaction, duration of interaction, and whether interactions were satisfying or not. Audio recordings were employed whenever there was an interaction between the observed subject and other people. Questionnaires were used to collect information about the organization, projects, and subjects involved in the observations. Unstructured interviews were conducted with the observed subjects in order to understand the subjects' activities or problems that occurred during the observation. The limitations and hindrances that occurred during the observations were as follows.

- The data not explicitly produced but eventually understandable in the interactions were context and incomplete sentences, which were later gathered by unstructured interviews with the subjects.
- The subjects sometimes interacted in languages that the observer was unable to understand.
- A digital voice recorder does not always record voice clearly when subjects are in motion.

In order to give a comparative view, Table 2 enlists the data collection methods and the corpus of data collected from industry by some of the previous researchers in this area. Most of them used data sheets to collect the information needs of designers. In

Table 1 Observed tasks and the design stages

Designers	Design stage	Tasks
Designer 1	Embodiment (202)	Design an injection mould for a given component
	Embodiment (118)	Design a low cost nonreusable injection syringe for medical applications
Designer 2	Conceptual (93)	Design a handheld mechanism for filling and removing a fluid without leakage and with ease of use
Designer 3	Task clarification (35)	Design a canopy of a tractor for ease of manufacture, reduced cost, and better aesthetics
	Detail design (358)	Analyze a door component of a cold storage device in FEA software to study the heat transfer rate
	Conceptual (53)	Design an aesthetically pleasing holder for toothbrushes

Table 2 Comparison of methodology

Researcher(s)	Methodology	Data capture method(s)	No. of subjects	Total duration
Marsh [3]	Observations	Data sheets	12	17 days
Nidamarthi [26]	Observations	Data sheets, interviews	1 team	5.5 months
Ahmed [53]	Observations	Data sheets, audio recording	12	24 h
Court [54]	Observations	Data sheets, interviews	20 >200	Individual task
Aurisicchio [43]	Diary study, observations	Data sheets	12 10	60 weeks 70 h
Vijaykumar and Chakrabarti (This work)	Observations	Data sheets, audio recording, questionnaires, interviews	3+8	15 days (56 h)

Table 3 Taxonomy of knowledge

Categories	Factors
Topics	New and old Issues and proposals Data, information, and knowledge
Classes	Product based and process based Requirement, requirement-problem, solution, solution-problem, and requirement-solution Function, structure, behavior, complete product and purely process related Property, value, material, assembly, component, interface, feature, manufacturing, location, method, document, people, and schedule
Activities	Problem understanding and problem solving Generate, evaluate, and select
Questions	Descriptive (answer is elaborate) and point (answer can be yes or no).

our experience, collecting required data through data sheets alone was difficult, less comprehensive, and less efficient because of the speedy nature of interactions between designers. It has been observed that the average numbers of questions captured through diary study and personal observations with data sheets were 3 per day and 3 per hour, respectively [43], whereas our observations with audio recording yielded about 15 questions per hour. Ahmed [53] used audio recording in a modified environment (asking individuals to think aloud) rather than in natural settings. In our study, the environment was natural and designers were not disturbed by the observations. We argue therefore that amount of data collected in our study, which was in a natural environment, is substantially more than that in the previous cases.

5 Taxonomy of Knowledge

Since none of the classifications discussed in Sec. 2 provides adequate insight into the knowledge needs of designers, we propose a new taxonomy of knowledge needs. This is based on literature and other observations at study. The taxonomy has four broad categories of knowledge: topics, classes, activities, and how questions were asked, see Table 3. The goal of the taxonomy is to integrate the various representations proposed in literature for *deliberations* or *argumentations* made during the design process, *artifact* being designed, and the *activities* of the designers. Without integrating these purposes, the representations might not be beneficial to answer the four questions generated, see Fig. 1. In the spirit of argument in Ref. [55], all terms used in the taxonomy are explained in Ref. [57].

In the *topics* category, contextual factors, i.e., the nature of questions, are considered. To represent the moment of time, *old* and *new* are used. These terms were used in Ref. [28] in the category of *age of topic*. To consider the argumentative approach, existing models such as IBIS, QOC, PHI, and DRL were analyzed. It was found that issues or questions, proposals or alternatives, and arguments or justifications are commonly considered in these approaches. In our study, we observed that arguments or justifications could also be classified in terms of issues and proposals. So, we ignore the argument factor in our taxonomy. By analyzing the many definitions of knowledge, information, and data in literature, we conclude that for studying the types of questions asked by designers, we must define the terms in relative, rather than absolute sense. We use the relative definition proposed in Ref. [56], see Fig. 2. Since knowledge is derived from information and data, all three terms were included under topic category.

In the classes category, artifact being designed is classified in a hierarchical structure. All the groups except the second one in the

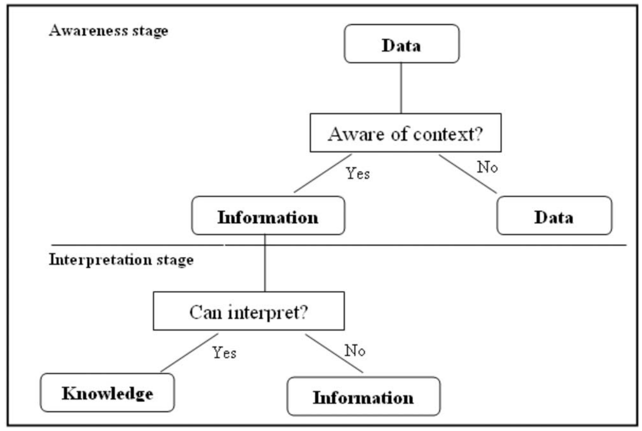

Fig. 2 Definition of data, information, and knowledge [56]

classes category are derived from literature discussed in Sec. 2. That group was deliberately constructed to avoid any confusion existing in literature among the terms problems, requirements, and solutions. We note that problems could occur with both requirements and solutions. The other factors (not found in literature) added to the groups are complete product, purely process related, method, document, people, and schedule. In addition to structure, behavior, and function classification, complete product and purely process related factors are included to accommodate the following sample questions: "which concepts will best satisfy the requirements?" (complete product-related query) and "how you have done this task?" (purely process related query).

In the activities category, the terms used in Refs. [25,26] are particularly well suited to describe the knowledge needs of designers. The category how questions were asked is used to describe the kind of answers expected from the questions. To avoid more number of factors given in Ref. [30], it is classified into *descriptive* and *point*. The point questions demand *yes* or *no* confirmations and *fill-in-the-blank* answers, whereas descriptive questions demand more explanations and justifications. Based on the definitions of the factors used in the taxonomy (Ref. [57]), and on the analysis of the questions asked by the designers, we argue that the factors in each group under each category are mutually exclusive.

6 Results

We captured 859 questions in the various tasks observed (Table 1). The questions were either asked by the three designers observed or asked by one or more of the eight other designers interacting with the observed designers. In the organization observed no document other than computer-aided design (CAD) files was generated or recorded formally during design. None of the 859 questions was recorded, or recorded in a formal document. So, analysis of all the questions asked should help answer what knowledge is developed but not captured that should be otherwise. Table 4 represents the needs of the designers, as identified by analyzing the 859 questions asked by the designers using the proposed taxonomy. In analyses, no questions categorize in *data* and *select* factors.

The major observations from Table 4 are as follows.

- Irrespective of the design stages, in almost 50% of the questions, designers interacted with others to know about old issues or proposals. Designer's time for designing would benefit considerably if the answers for these 50% of the old questions were captured and made available for retrieval in formal documents. This observation triangulates with the findings in Ref. [27]. They mentioned that designers required 51% of old information in the redesign work.

Table 4 Needs of the designers using the proposed taxonomy in various design stages

		Design stages				
	No. of questions analyzed	Task clarification 35	Conceptual 146	Embodiment 320	Detail design 358	Overall 859
Topics (in %)	Old	60	40	44	54	49.5
	New	40	60	56	46	50.5
	Issues	57	62	47	56	55.5
	Proposals	43	38	53	44	44.5
	Information	80	62	56	70	67
	Knowledge	20	38	44	30	33
Classes (in %)	Product based	71	68	71	43	63.25
	Process based	29	32	29	57	36.75
	Requirement	49	8	1	10	17
	Requirement-problem	14	1	1	1	4.25
	Solution	34	73	84	71	65.5
	Solution-problem	0	8	10	17	8.75
	Requirement-solution	3	10	4	1	4.5
	Function	37	4	0	4	11.25
	Structure	28	45	83	56	53
	Behavior	6	24	2	6	9.5
	Complete product	0	2	9	1	3
	Purely process related	29	25	6	33	23.25
	Feature	8	35	46	32	30.25
	Property	40	4	9	8	15.25
	Value	0	3	3	15	5.25
	Material	0	2	1	0	0.75
	Assembly	0	6	4	2	3
	Component	36	31	24	21	28
	Interface	0	1	4	2	1.75
	Manufacturing	0	2	3	2	1.75
	Method	0	0	0	4	1
	Location	4	5	6	6	5.25
	Document	12	8	0	3	5.75
	People	0	2	0	2	1
	Schedule	0	1	0	3	1
Activities (in %)	Problem understanding	71	4	0	13	22
	Problem solving	29	96	100	87	78
	Generate	80	71	73	78	75.5
	Evaluate	20	29	27	22	24.5
Questions (in %)	Point	37	50	75	61	55.75
	Descriptive	63	50	25	39	44.25

- Even though the number of issues raised by the designers in all stages of design was higher than the number of proposals, the proposals played a vital role in the questions analyzed. It shows that considerable proportion of time was spent by the designers on validating, by asking questions, the answers known to them.
- The information needs were much higher than the knowledge needs of the designers. It means that designers mostly tried to be aware of the issues and proposals rather than interpreting them.
- The designers' need for product-related information or knowledge was much higher than that for process-related information or knowledge. That is, designers focused more on the artifact being designed than on how to design it. This indicates that concentrating on capture and reuse of product-related information or knowledge could substantially enhance a designer's efficacy during design.
- The variation in the information or knowledge needs of the designers across the stages of design was observed in all groups of the classes except the product-process group. Even though requirement queries were higher in the task clarification stage as expected, the substantial number of solution-related queries in this stage shows the designers' tendency toward problem solving. As design progressed, the number of solution-related queries was substantially increased. The efficacy of the designers is represented by the considerable reduction in the number of queries related to *requirement-problem* factor after the task clarification stage. The queries linking the artifact being designed with requirements considered for assessing the solution were less than the other factors in that group.
- Structure-related queries played an important role in all stages of design, whereas function and behavior have been higher in the task clarification and conceptual stages. Designers also concentrated on *purely process related* information or knowledge throughout the design process.
- Except in the task clarification stage, feature-related queries were more frequent than the other factors in that group. Again, the findings in Ref. [27] match with our observation. They found that designers frequently concentrate on the finest level of detail, i.e., feature. Apart from the feature-related queries, queries related to property and component were also considerable throughout design.
- As expected, queries related to problem understanding dominated the task clarification stage, while problem solving dominated the rest of the design process.
- Designer's queries showed that they asked more questions

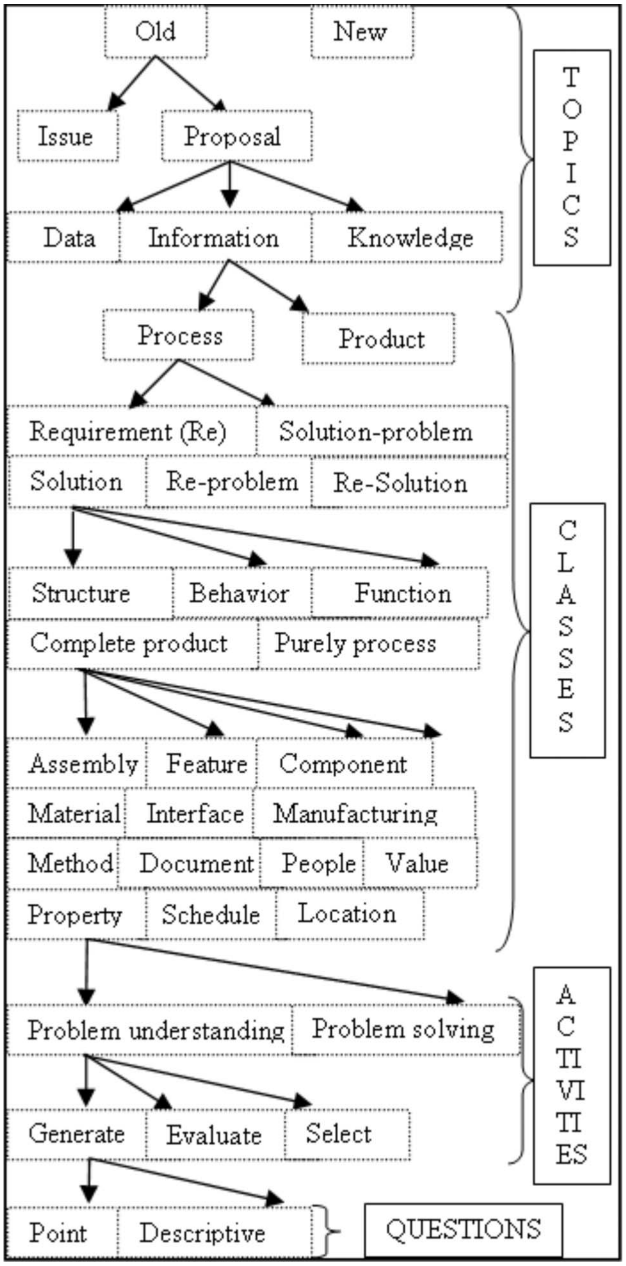

Fig. 3 Combination between the categories

on generating issues or proposals rather than on evaluating them, in all design stages.

- The answers sorted by the designers through questions were mostly point based rather than descriptive. This correlates with the earlier point that designers often try to validate the answers known to them.

Use of single categories from the proposed taxonomy for structuring knowledge, while being more generic in scope than previous taxonomies, still provides a limited view of the structure of the knowledge needs of designers. Factors from each category must be combined to create more detailed structures with which knowledge generated can be better represented and distinguished. In Sec. 7, we propose an approach to convert the questions asked into a generic form by using such factor combination.

7 Generic Questions

Possible combinations between the categories are proposed in Fig. 3, which represents one sample combination, from those possible using the taxonomy of knowledge, by choosing a single factor from each category. The figure can be extended to represent all potential combinations. Using such combination, we convert each question, asked by designers, into a generic form. For example,

I see the wall thickness here. Why it is?

This question was categorized by the knowledge factors below. The reasoning for selecting the particular factors is explained within the parentheses.

Issue (concern without solution)→knowledge (intended to interpret)→old (issue considered before)→product (concern about artifact)→structure (concern about a part)→solution (concern about artifact without problem)→feature (concern about particular element)→location (concern about position)→problem solving (finding solution to satisfy requirements)→evaluate (intended to assess)→description (required a detailed answer)

Since inclusion of all the categorized factors into the question will lead to considerable complexity, we included only those that are essential for interpretation of the question in the generic form, and kept the other factors in parentheses for understanding the context of the question. The above question was transformed into the following generic form:

Why this feature in that location? (issue, knowledge, old, product, structure, problem solving, evaluate, description)

This question combines the various categories in the proposed taxonomy in a specific way. Figure 4 represents the relationships that exist among factors for the last group in classes. Each arrow represents an "of" relationship between the starting and the end node of the arrow. For instance, an arrow from "location" to "feature" reads as "location of feature." The answer to this generic question helps answer the research question: What knowledge is developed but not captured that should be otherwise. Other benefits of creating generic questions were as follows: It aided in consolidating the questions and reduced the apparent variety among the questions by 56%. Tables 5 and 6, respectively, illustrate the distribution of questions under product- and process-related queries. All generic questions so generated are in Ref. [57]. Only one other research focuses on generic questions [30]; we classified their questions using our categories for comparing the two findings (Tables 5 and 6). The Gruber and Russell's generic questions, along with that of ours (in italics), are in Ref. [57].

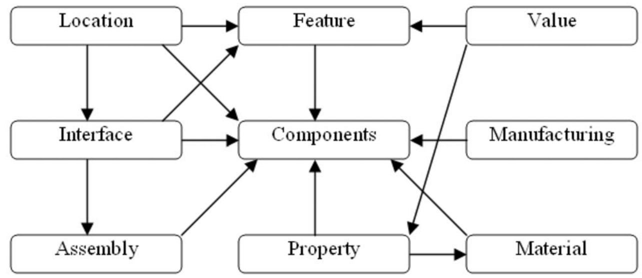

Fig. 4 Relationships between factors in the last group of the category "classes"

Studying the distribution of generic questions (using our classification, Tables 5 and 6), we find the following.

- In generation of product-based knowledge, designers mainly wished to be aware of issues and proposals rather than to interpret them, except when generating new knowledge of proposals; during evaluation, however, their main interest was in interpreting issues and proposals.
- In generation of process-based knowledge, designers were interested mainly in new and old issues rather than proposals, to be aware of and interpret them; in evaluation, they

Table 5 Distribution of questions: product related

		Product related							
		Our study=506				Gruber and Russell's work=58			
		Issues		Proposals		Issues		Proposals	
Total questions		Old	New	Old	New	Old	New	Old	New
Generate	Information	109	52	124	12	33	1	0	0
	Knowledge	5	33	0	58	0	5	0	3
Evaluate	Information	0	0	13	0	0	0	5	0
	Knowledge	16	36	14	34	6	3	0	2

focused, as expected, primarily on new and old proposals rather than issues.

Tables 5 and 6 show that our factor combinations can classify all the generic questions from Ref. [30]. We also observe that, except for the classification of product based knowledge to generate awareness about old issues, not many questions are found in Ref. [30] to fall in other categories in our classification. This could be due to the limitation in variety of data analyzed in Ref. [30], which was largely from laboratory settings, as opposed to industrial data in our case illustrating the wider variety possible in reality.

In this work, data collection and analysis did not allow us to identify the relative importance for capture across various kinds of knowledge generated during design. However, it highlighted which kinds of knowledge were primarily sought, indicating that capturing and structuring of these should substantially reduce the amount of time spent by designers in knowledge acquisition and dissemination.

8 Discussion

The eventual aim of this study is to satisfy information and knowledge needs of the designers during design process. The observation reveals that nearly 50% of the old queries were answered by colleagues. This designers' behavior would significantly impact the design time as it consumes time of their colleagues also. To understand this behavior better, we need to compare the questions analyzed in this paper to the knowledge captured in the formal documents and the relevant computer-based systems that are accessible to designers, which are not available in our study. This comparison would reveal if the required knowledge are captured in the currently available systems. However, we found that CAD systems did not fulfill the information needs of the designers since even with CAD models available, significant number of queries arose on identification, verification, and visualization of these models.

We argue that current information- and knowledge-based systems should be modified by considering the requirements of designers, with more emphasis on information-based systems. This conclusion matches with findings in Ref. [43] that "direct retrieval-recognition" queries were more compared to "reasoning based" queries. The systems should focus more on issues or proposals related to generation of product-related information. Validation plays a vital role in knowledge processing activities. In this sense, systems should help confirmation of proposals put forward by designers.

We feel that the most important prerequisite for knowledge processing is a good representation of knowledge, as this would influence all knowledge processing activities. Literature suggests that most knowledge representations are evaluated for their expressiveness of purpose. Being able to analyze and categorize all 859 questions using our proposed taxonomy demonstrates its expressiveness. Another criterion for evaluating a representation is its intuitive appeal to designers, which we intend to use in the future.

9 Conclusions and Future Study

With a model of relations between knowledge as basis, a set of research questions was formulated to develop the understanding needed for enhancing knowledge reuse during design. Focusing on the research question—what knowledge is developed but not captured that should be otherwise—a taxonomy of knowledge needs of designers is proposed. Using the taxonomy, the questions asked by designers were transformed into a generic form, which helped validate the taxonomy and highlight primary aspects of knowledge needs of the designers involved at various design stages. The taxonomy must be validated further and made exhaustive using other product development stages and with other designers. While the subgroups within each category of the taxonomy are mutually exclusive, the exhaustiveness of the categories is yet to be confirmed. Further work involves doing the above and using the taxonomy as a basis for supporting capture and structure of knowledge generated during design for enhancing its reuse.

Table 6 Distribution of questions: process related

		Product related							
		Our study=353				Gruber and Russell's work=7			
		Issues		Proposals		Issues		Proposals	
Total questions		Old	New	Old	New	Old	New	Old	New
Generate	Information	59	58	20	31	2	1	0	2
	Knowledge	10	42	0	38	0	1	0	1
Evaluate	Information	10	9	26	19	0	0	0	0
	Knowledge	11	7	0	13	0	0	0	0

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