INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'07
28 - 31 AUGUST 2007, CITE DES SCIENCES ET DE L'INDUSTRIE, PARIS, FRANCE

UNDERSTANDING PATTERNS OF INTERACTION BETWEEN DESIGNERS DURING DESIGN PROCESS

Gokula Vijaykumar A.V[1] and Amaresh Chakrabarti[1]

[1]IdeasLab, Centre for Product Design and Manufacturing, Indian Institute of Science, India

ABSTRACT

Collaborative design is particularly important, in this globalize world, in aiding organizations in satisfying customer requirements through high innovation, reduced cost, high quality and lesser time to develop products. Communication is a major factor in collaboration, and its quality is heavily influenced by the quality of interaction. Various kinds of interaction are found in a design process. However, little work is available in assessing their quality. We emphasise the importance of interaction with the help of a collaborative model developed for understanding knowledge generation activities. The intent of this paper is to study the patterns of interaction among designers in communication with each other during product development process which will aid to assess their quality. We generate types of questions and answers by analysing two different kinds of interaction captured from industry. In the results of analysing these interactions we have developed a generic interaction model of questions and answers. We argue that this model should be helpful to understand the patterns of interaction in any stage of the design process. We argue that by enhancing the quality of these interactions customer requirements mentioned above can be satisfied more efficiently.

Keywords: Collaborative design, communication, interaction

1 INTRODUCTION

The current design scenario of ever increasing customer requirements and continuous reduction in product life cycle forces companies to develop more complex and innovative products with high quality and low cost concurrently in order to meet the decreasing time to market. Globalization is here to stay and more so in the area of product development. Today, as experienced by many industries, not only the resources and equipment, but also knowledge and expertise are geographically distributed. To overcome these challenges companies should utilize all competence available, work in teams and scout for talent across the globe.

According to Wang et al. [1]: *when a product is designed through the collective and joint effort of many designers, the design process is called collaborative design.* There are many factors influencing successful collaborative design, e.g., knowledge, information, communication, decision making, process management and social issues. Ostergaard & Summers [2] propose taxonomy of factors influencing collaborative design. The attributes, which compose the top level of the taxonomy, are team composition, communication, distribution, design approach, information and nature of problem. Communication is a major factor in collaboration, and its quality is heavily influenced by the quality of interaction. Communication is the process by which information is shared so that work is accomplished. Brereton et al. [3] argue that the content of an evolving design depends crucially upon negotiation strategies and other subtle and ubiquitous social interactions. Some of the factors causing communication failure are misinterpretation, ambiguity and uncertainty. Various kinds of interaction are found in a design process. However, little work is available in assessing their quality.

The intent of this paper is to emphasise the importance of interactions and to study the patterns of interactions among designers in communication with each other during the product development process, which will aid to assess their quality. Normally collaborative design is classified with respect to time and space. Table 1 represents this classification and focus of this paper. The paper focuses on synchronous interactions occurring at the same location because this kind of interactions happen most frequently and occupy most of a designer's time during the product development process.

The subsequent discussions in this paper are organized into six sections. Section 2 provides a detailed literature survey about interaction and the relevance of this paper. Section 3 discusses research questions addressed in this paper. Section 4 discusses the approach followed to answer the research question framed. Section 5 emphases the importance of interactions will the help of a collaborative model developed for understanding knowledge processing activities. Section 6 elaborates the types and patterns of questions and answers occurred in interactions and a generic interaction model developed to understand patterns of interaction. Section 7 presents conclusions from these observations and future work to be carried out.

Table 1. Types of Collaboration & Focus of this paper

Time \ Space	Same Place	Different Place
Same Time	✓	
Different Time		

2 LITERATURE SURVEY

In this section we detail the needs to understand interactions and its patterns and how interactions influence designs during the product development process.

2.1 Importance of interactions

Larrson et al. [4] observe that one to one conversations are common in co-located teamwork and they serve as a natural part of creative teamwork. Frankenberger & Badke-Schaub [5] observe that in design, designers spend more time individually than in teams but critical situations occur in collaboration. They demonstrate the importance of group communication and informal conversation. Eckert et al. [6] observe how failure to achieve appropriate information flow in large-scale engineering design processes contributes to a variety of problems for designers and decision-makers. The manifestations of inadequate information flow are: not understanding the big picture, not knowing what to know, information distortion, and difference in interpretation of representations.

Brereton et al. [3] investigate how social interactions shape a product: the content of an evolving design depends upon negotiation strategies and other subtle and ubiquitous social interactions. Team members' orientation to a solution or process is demonstrated by the levels of commitment in utterances; team members continuously engage in monitoring multiple issues at multiple levels of attention. Cross [7] investigates a teams' ways of planning a design process, gathering/sharing of information, and developing and adopting design concepts. He observes that planning is often tacit, information sharing is informal, roles and relationships play an important role in social interactions, and opportunistic behaviour is often a hindrance to teamwork. Whittakar et al. [8] found that 50% of opportunistic face-to-face interactions lasted less than 38 seconds, and that they lasted only 1.89 minutes on average. The cycle of communication is fast; problems are dealt with as they come up, and information is exchanged as a natural, effortless and integral part of everyday work. Fundamentally, the iterative style of informal communication enables people to reach well-founded decisions and find common ground more rapidly than through conventional meeting structures. Enestrom et al. [9] argue that factors that influence co-operation are involvement in the early phases, personal contacts especially face-to-face contact and open discussion between the people involved in the design process. They conclude that communication as an important factor for good co-operation.

2.2 Patterns of interaction

Nakakoji et al. [10] look at the relationships between evolution of design artefacts and communication between collaborating designers. In particular, they look at communication in terms of *intent* (the meaning behind the message) and *context* (the background against which the message is articulated and understood). To describe the process of communication of intent, they use the terms *speakers* and *listeners* to refer to two roles: those who articulate their intent and those who try to understand (assign a meaning to) the articulated representation, respectively. They argue that if the listener uses a context that is different from the one that the speaker used (and this is true for most cases) when interpreting

the representation, miss-communication occurs. They suggest that designers must be able to represent intended concepts directly and distinctly using familiar notations and languages. Beyer et al. [11] argue that basic patterns of communication include information object communicated, its means of communication, sender and recipient. The objectives are to inform oneself, to ask, to provide information, to forward information, to inform somebody, and to exchange information. Wu & Duffy [12] develop a model to present information flow in design based on Situation Theory. The model includes *input information of sender(s) and receiver(s), interaction between agents, output knowledge of agents, the goal of interaction, and the goal of sender and of receiver*. They argue that this model helps analyze design information systems and provides a basis for investigating the situatedness of design information flow.

Minneman [13] addresses ways in which design work emerges from interactions among individuals and groups as they establish, develop, and maintain a shared understanding. Negotiating understandings, conserving ambiguity, tailoring engineering communication for recipients and manipulating mundane representations are identified as crucial group activities. Trousse and Christiaans [14, 15] analyze the role of argumentation in complex problem solving. They categorize a meaning-construction space into structural space, socio-linguistic space, and discursive space. They hypothesize that the knowledge structure and expertise of each designer can be demonstrated by analyzing the discursive space, an important component of design rationale. They argue that the rate of success not only depends on the knowledge inputs but also on social processes within the team. Senge [16] discusses how reinforcing/balancing feedback loops enhance learning processes. The concept of high-level interactivity is really analogous to a dynamic feedback loop that reinforces learning. MacGregor et al. [17] found that interactions between engineers for information exchange (IE) and collaborative design (CD) are in a ratio of approximately 5:1; IE is characterized by asynchronous interaction, while CD in a synchronous fashion. These two interact cyclically.

According to Schoen's theory [18], designers work in an alternating cycle of action and reflection. The designer *acts* to shape the design situation by creating or modifying design representations, and the situation "talks back" to the designer, revealing unanticipated consequences of the design actions. In order to understand the situation's back-talk, the designer *reflection* the actions and consequences, and plans the next course of action. Thus, designers are speakers when they act on a design representation and listeners when they reflect on the representation. This interaction between designers as speakers and designers as listeners drives the evolution of artefacts.

Kleinsmann & Valkenburg [19] identify barriers of communication in collaborative design in three levels: participants, project, and organizational. Most barriers occur in the conceptual stage at the participant level, validation phase at the project level and definition phase at the organizational level. Eppinger & Salminen [20] introduce three views of product development complexity: process, product and organization view, and learn about the complex social phenomenon of product development by studying patterns of interaction across the elements within each view. They find that even where the development process shows uni-directional information transfer, the actual communication between individuals are predominantly bi-directional exchanges. Eckert & Stacey [21] categorize the variety of interaction in design by the dimensions of communication situations: *form of communication, form of task, subject expertise, tool expertise, organization, and representation of information*. They argue that no single approach to support communication is sufficient to handle the richness and variety of possible communication acts. Stacey & Eckert [22] propose typology of forms of uncertainty in design communication as: *precision, typicality, commitment, sensitivity, input confidence, understanding and confidence*. They argue that managing uncertainty in design is possible by supporting informal channels, understanding task dependencies, assembling negotiation groups, assessing the power of design representations and supporting asynchronous negotiation through the transmission of meta-information. Chiu [23] investigates the role of organization in collaborative design communication; vertical subdivision of work is found easier and better performing than horizontal subdivision. Communication problems observed broadly include *media, semantics, performance and organization*. He concludes that a structured organization can facilitate design communication, contributing to the success of the design project.

Thoben et al. [24] propose the Formal Interaction Analysis model for improving the availability of information by creating awareness about existing problems, and sensitising about benefits of available information, and by providing a decision support for analysing, designing and selecting appropriate

communication means and communication patterns. They consider *task, information need, information and its characteristics, and communication means* as the basic elements of an interaction.
Harvey and Koubek [25] argue that communication research refers to the collaboration process as *referential communication*. To communicate successfully, one person must 'mutually accept' the other's references before the conversation proceeds. The effectiveness of the communication process is based on what is called *common ground* (Clark and Willes-Gibbs, 1986). The effectiveness of communication seems to be dependent on developing a shared vocabulary by which to communicate and requires further investigation to understand the collaboration process.
Eris [26] argues that designing is question-intensive. However, our knowledge of the role of asking questions in design is limited. He defines a question as: "*A verbal utterance related to the design tasks at hand that demands an explicit verbal and/or nonverbal response*". He illustrates a strong relationship, a duality, between questions and decisions. He reviewed, compared and extended the taxonomies of questions from four fields: philosophy, education, artificial intelligence, and cognitive psychology. Ahmed [27] shows pattern of interaction with the help of type of query asked by novice designers and responses given by the experienced designers, See Table 2.

Table 2. Experienced designers' response to a query

Type of query	Experienced designers response to a query
Question	Answer the question
	Answer the question and provide additional information
	Rephrase or state questions as irrelevant
	Rephrase or state questions as irrelevant and provide additional information
Statement	Rephrase or state as irrelevant
	Rephrase or state as irrelevant and provide additional information
	Provide additional information

Lehnert [28] argues that *question answering* is a fundamental human ability. When people speak to each other, a substantial amount of communication is achieved by asking and answering questions. People are largely unconscious of the cognitive processes involved in answering a question, and are consequently insensitive to the complexities of those processes. She presents a process model of question answering as a theory of conceptual information processing that includes 13 conceptual categories for questions.
Bales [29] develop system of categories and their major relations to study interaction of small groups which he terms as *interaction process analysis*. In that method he discusses about questions, answers and positive and negative reactions occurred in the interaction, and their respective problems. Figure 1 explains the Bales's interaction process analysis. He proposes a problem-solving sequence as a frame of reference in the order of questions, answers, negative reactions and positive reactions, see Figure 2. The numbers in Figure 2 are the numbers of the twelve categories shown in Figure 1.

2.3 Summary of literature survey

The research papers discussed in the previous sections address: importance of interactions, classification of design communication, media, and interactions, barriers of communication in different stages of collaborative design, patterns of communication, forms of uncertainty, and role of social interaction in design. Importance of interactions and communication and their influences on the evolving design are emphasised in the current literature. *Interactions will be efficient only if the intent and context of the utterances are properly transmitted between designers*. To do so, designers have to maintain shared understanding between them. Definition of interaction is not explicitly stated in any of the research papers. Interactions between the designers are studied with respect to the patterns of queries and responses. But types of queries and responses considered are limited and their impact on the product development process and outcomes are not studied in detail. Even though importance and influences of interactions are presented in the literature, its impact on the overall design process is not addressed. The subsequent sections address some of the gaps found in this literature survey.

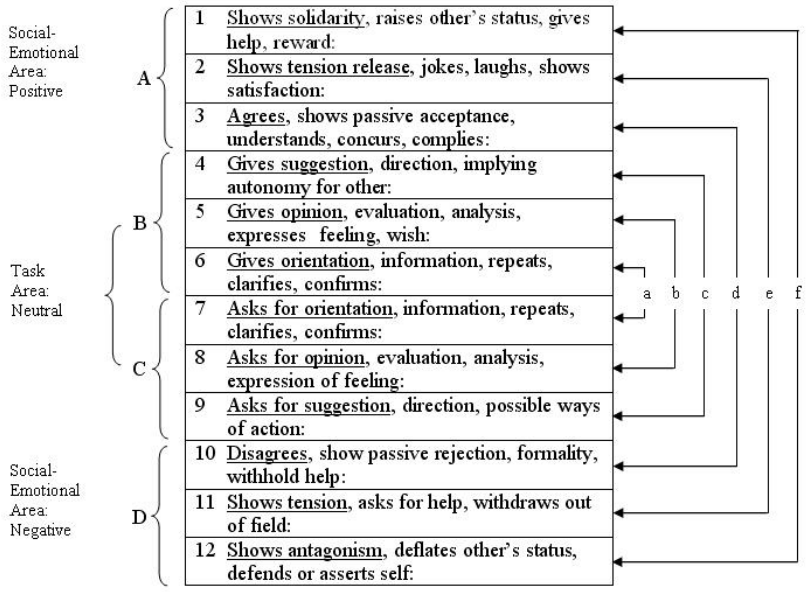

Figure 1. Bales's system of categories & relations

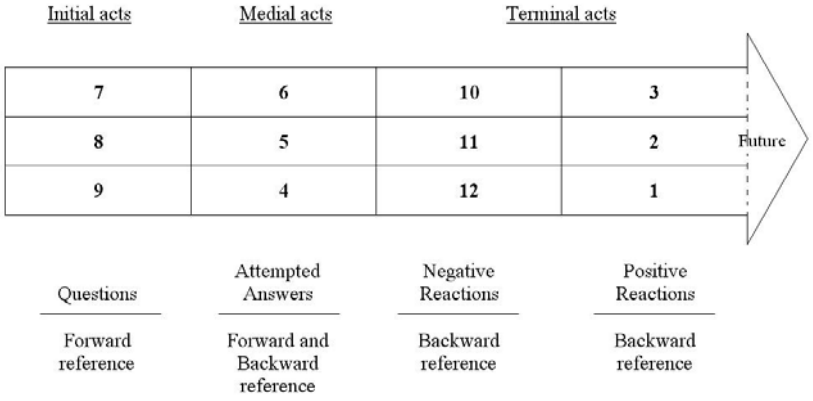

Figure 2. Bales's problem-solving sequence

3 RESEARCH QUESTION

Since the impact of interactions on the overall design process is not detailed in the literature we will address the significance of interaction with the help of a collaborative model which is developed to understand knowledge generation processes. The primary objective of this paper is to understand the patterns of interaction during design processes in industry which will aid to study their quality. It is possible to measure the quality of interactions in two ways (i) by environmental factors such as composition and capabilities of the workspace (orientation, amount of simultaneous access and proximity), the time scale of task and the stage of development, the working dynamics of the group and group size [30], and (ii) by the content generated during interactions. In this paper the focus will

be on the content generated during interactions in the design process. The term 'interaction' is not adequately defined in engineering design literature. We define 'interaction' as '*a mutual or reciprocal action or influence of agents to produce or exchange, or intended to produce or exchange knowledge or information*'.

4 APPROACH

In order to understand the various patterns within the different types of interaction, we carried out a case study in an industry. Designers involved in different projects were observed for a week each. The methods employed to collect the required data were questionnaires, unstructured interviews, voice recordings, video recordings, desktop sharing and data sheets. Questionnaires were used to collect information about organization, projects and subjects involved in the observations. Unstructured interviews were conducted with the observed subjects whenever it was necessary to understand the subjects' activities or problems that occurred during observation. Voice recordings were employed whenever there was an interaction between the observed subject and other people. Video recordings were used to capture the data generation during the complex interactions that involved two or more people with documents or other information sources. Desktop sharing was used to capture the subjects' interactions with the computer. Data sheets gave details about the purpose of the tasks, interactions, place of interactions and duration of interactions. Even though there are various types of interaction found in a design process, we particularly address in this paper those interactions in which two or more designers communicate orally with each other. We analyzed these interactions because this type of interactions is found to be the most frequent as well as most time consuming in a design process. Gestures & postures involved in the interactions are not considered in this work. In this paper, two interactions involving two designers and three designers respectively, discussing about the development of a design for thirty minutes each, are analysed and presented.

5 IMPORTANCE OF INTERACTIONS

A descriptive collaborative model has been proposed to illustrate the designing and knowledge operations through interactions. Figure 3 describes the collaborative model and influence diagram. In this model, requirements satisfaction has been considered as a primary objective of an engineering design process, because satisfying design requirements achieve the customers' needs, apart from enabling the development of a design into a product [31]. Each requirement consists of a set of tasks with purposes and outcomes, and is executed through a complex variety of interactions. For example, a designer may have to interact with another designer, clients, tools, groups of designers, or groups of clients. Each interaction may lead to new tasks, and will involve various knowledge operations: knowledge production or updating, sharing, storage, structuring or reuse. Requirements, tasks, interactions and knowledge will influence each other in the consequent order.

The hypotheses are that the purpose of the tasks will be satisfied only if a designer is able to get, produce, share, and reuse knowledge properly (knowledge satisfaction) through effective interaction (interaction satisfaction); the satisfaction of every purpose of the tasks will influence the requirement satisfaction of the artifact. In this competitive scenario requirements of an artefact should get satisfied in a resource effective way. The resources can be clubbed into two categories: time and cost. The set of tasks, interactions and knowledge will get influenced by available resources. We can say that the quality of interaction is good, only if it satisfies the purpose of the tasks in a resource effective way. Thus, the model emphasises the importance of interactions in the overall design process. Types of interactions observed during case studies are *designer alone, designer with documents, designer interacting with computers, designer with computers and documents, designer with another designer, designer with many designers, designer interacting with another through phone, designer referring documents and interacting with another through phone, designer interacting with another in front of documents, and designer interacting with another in front of the computer*. In this paper two interaction types: *designer interacting with another in front of the computer and designer interacting with other two designers* were analyzed.

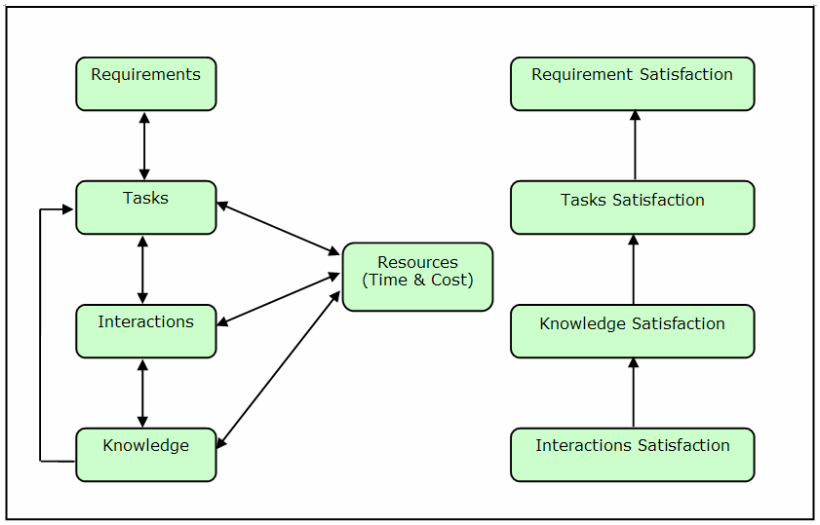

Figure 3. Collaborative Model and Influence diagram

6 TYPES OF QUESTIONS & ANSWERS

Two patterns are used in order to assess the quality of interaction: (i) the question-and-answer patterns that emerged during interactions and the (ii) Generate-Evaluate-Select cycle performed by the designers. From the protocol analysis of the two interactions captured during the design process, we classified various types of questions asked and types of answers given. Table 3 lists the types of questions and answers. The types are not defined because these are self explanatory.

Table 3. Types of question and answer

Types of question	Code No	Types of answer	Code No
New question	1	Not answered	10
New question to the question	2	Answered	11
Question for confirming answer	3	Answered for modified question	12
Question from the answer given	4	Answering for question that is not asked	13
Question to understand question	5	Answering question asked previously	14
Question for clarifying answer	6	Agreeing with the answer	15
Question with alternative answer	7	Clarifying the answer	16
Old question	8	Refuting the answer	17
Old question with alternative answer	9	Giving alternative answer	18
		Refuting the question	19
		Justifying the answer	20
		Repeating answer	21
		Incomplete answer	22

We have segregated the protocol with respect to the types of question and answer mentioned in Table 3. The percentage of each type of questions and answers for the two interactions are shown in Figures 4, 5, 6 and 7 respectively. Protocol analysis of the interactions revealed the following:

- In the question types, '*new question*' and '*question clarifying answer*' have a major share.
- In the answer types, '*answered*', '*answering for question that is not asked*', '*agreeing with the answer'* and '*clarifying the answer*' have a major share among others.
- A key finding is the dominance of '*questions clarifying answers*', which we believe to be a useful way of visualization of problems and solutions and perception of new problems.

- Another key finding is the dominance of '*answering for question that is not asked*'. This indicates – we argue – the perception of new aspects in problems or solutions not envisaged before (while formulating the question), and is a useful way of visualization and perception of problems and solutions. Lehnert [28] argues that the more inferences an answer carries, the better the answer is. We argue that designers are giving more inferences in their answers to give better response which in turn will aid to reduce the number of questions being asked.

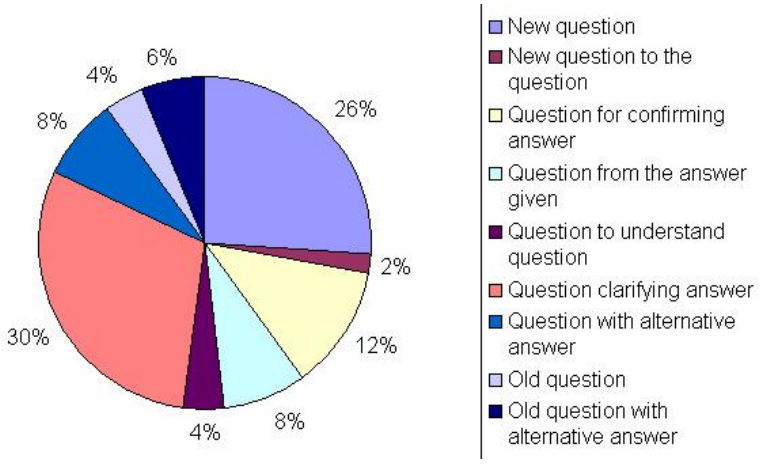

Figure 4. Percentage of types of question in interaction - 1

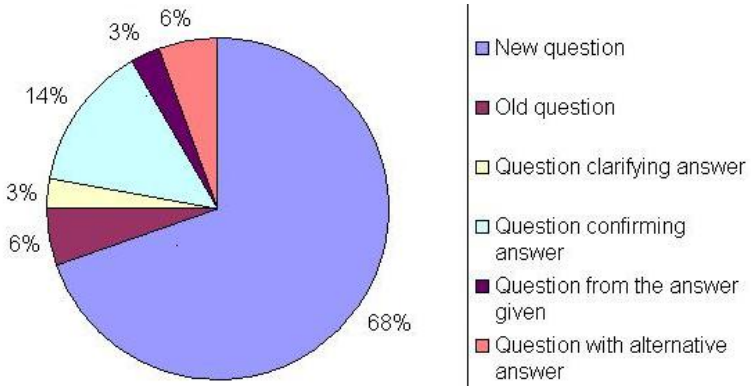

Figure 5. Percentage of types of question in interaction - 2

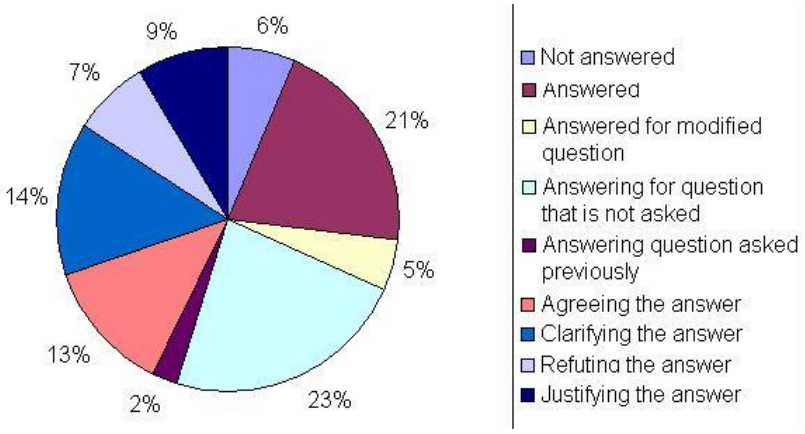

Figure 6. Percentage of types of answer in interaction - 1

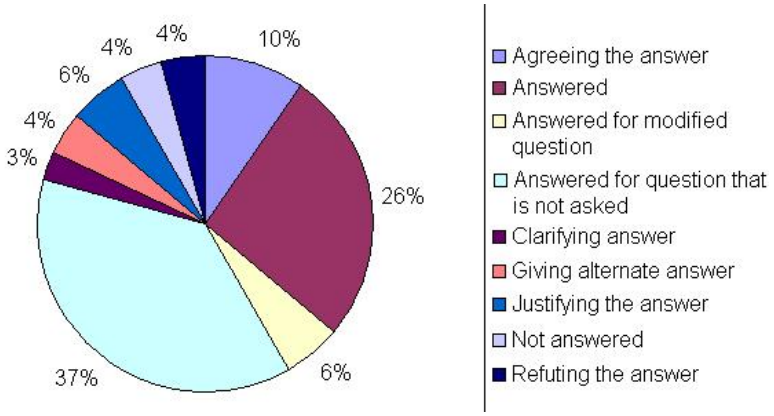

Figure 7. Percentage of types of answer in interaction - 2

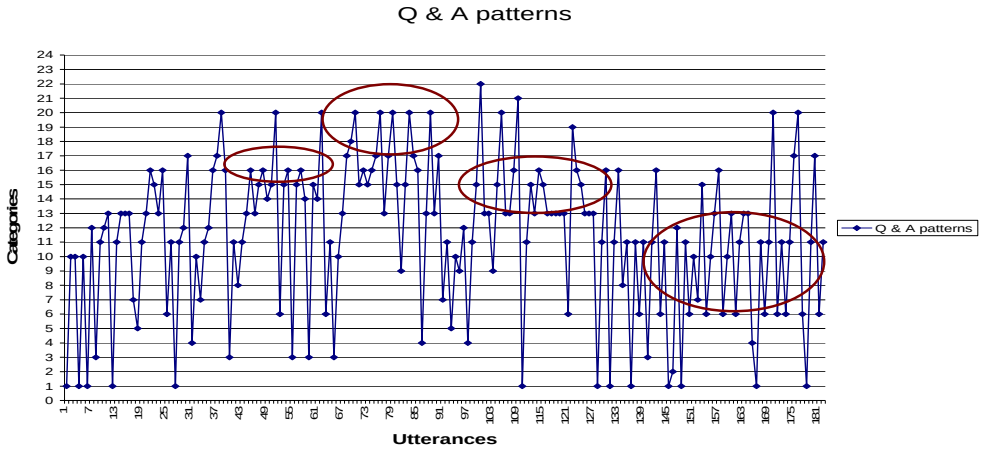

Figure 8. Patterns of questions & answers in interactions – 1

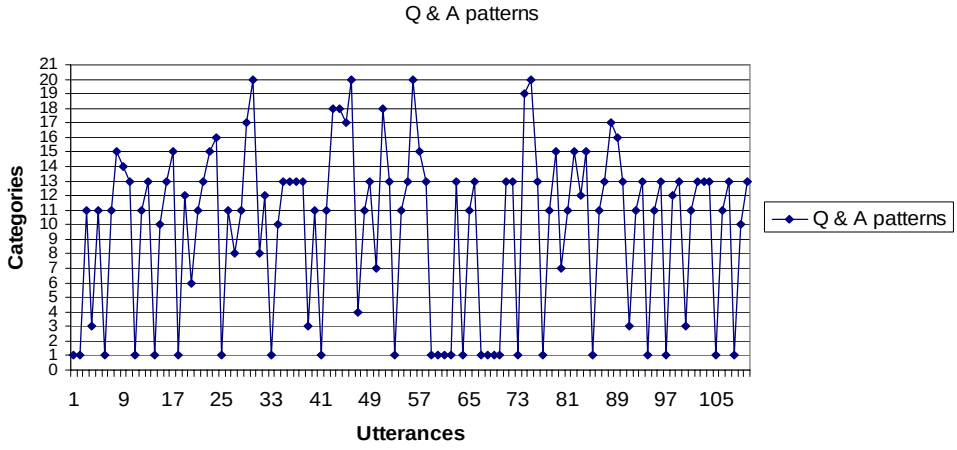

Figure 9. Patterns of questions & answers in interactions – 2

Figure 8 and Figure 9 represent the patterns of questions and answers occurring in the interactions analysed during product development process. The y-axis for both figures represents the categories code mentioned in Table 3 and x-axis represents utterances of the designers which are categorized. The patterns are very complex and ill structured. Some of the patterns that occurred in the first interaction are shown with the help of the ellipses in Figure 8. The patterns emerging are:

- *Clarifying the answer* preceded by *agreeing with the answer*,
- *Refuting the answer* preceded by *justifying the answer*,
- *Answering for questions that is not asked* preceded by *agreeing with the answer* and
- *Question for clarifying answer* preceded by *answered*.

These results show the tendency followed by the designers in the interaction. We expected that good interaction will follow the Generate-Evaluate-Select cycle, but no patterns emerged in the analyses. We developed a preliminary generic interaction model of questions and answers by analyzing the protocol with the help of types of questions and answers. This model could help us understand the patterns of interactions in all stages of product development. Figure 10 describes the generic interaction model of questions and answers. Both interactions analysed in this paper were initiated by a question. The first phase of the interaction is to understand the question asked and check its validity. The outcome of this phase will be to find the answer for the question or refuting the question itself. Refuting question will end the issue being raised and it will aid to shift to other issues. The second phase will lead to finding answers for the question asked. Various types of processes involved in finding answers are given in Figure 10. The outcomes of this phase might be to find (i) new questions based on the answer given, (ii) questions to clarify and confirm the answer and (iii) validity of the answer. Phase 3 should solve all the issues related to the answer proposed in phase 2 before proceeding towards validating that answer. Once all the issues related to the answer are discussed and analyzed, in the phase 4 decision will be taken to adjudge whether to agree with the answer or to refute it. Refuting the answer might lead to a justification process which again might lead to agreeing with the answer, or to generate more issues to be considered for taking decisions on the answer proposed. This interaction model of questions and answers is a preliminary understanding, obtained by analysing the protocol of the two interactions that occurred in industry. We need to study more interactions in order to validate the proposed interaction model.

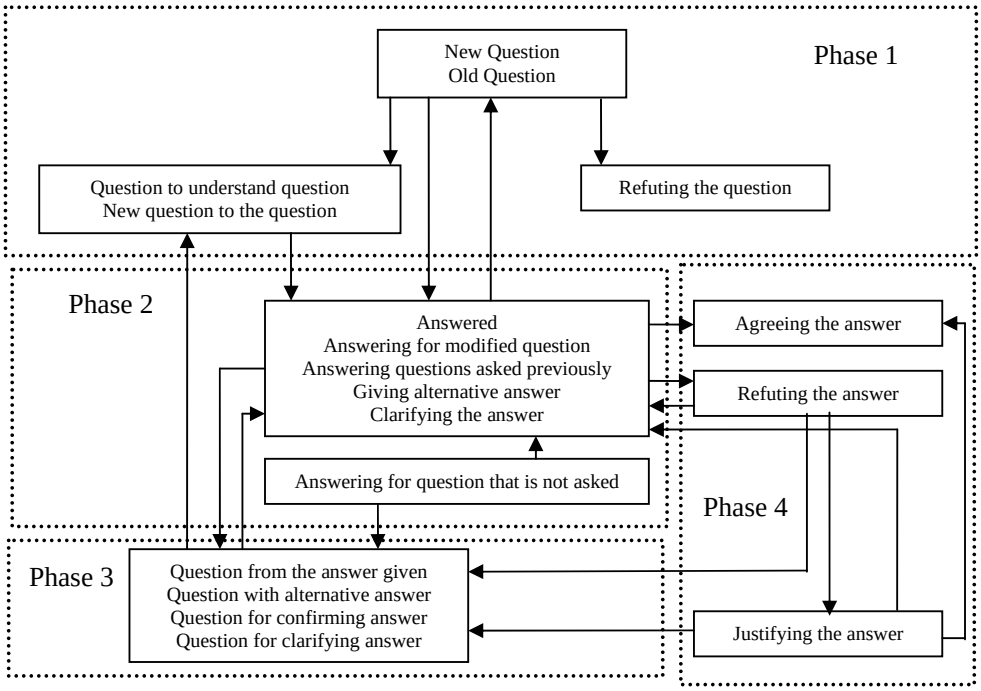

Figure 10. Generic interaction model of questions & answers

7 CONCLUSIONS & FUTURE STUDY

In this paper we emphasise the importance of interactions and its patterns and its influence on product development processes and outcomes. Various types of interaction found in industry are discussed. The patterns of interaction are studied with the help of types of questions and answers found in the protocol study. The importance of specific types of questions and answers are stressed with respect to the product development activities. From the analysis we developed a generic interaction model of questions and answers applicable to any stage of the product development process. We believe that

this type of classification would help in understanding the interactions between designers in an efficient way. We plan to validate these observations by analyzing more number of interactions between designers. In future we will address the quality of interactions by extending this work to study the impact of these patterns of interaction on the requirement satisfaction of the artefact designed.

REFERENCES

[1] Shen W. Xie H. Neelamkavil J. and Pardasani A. Collaborative conceptual design – state of the art and future trends. *Computer-Aided Design*, 2002, 34(13), pp.981-996.

[2] Ostergaard K.J. and Summers J.D. A taxonomic classification of collaborative design. In *International Conference on Engineering Design, ICED '03.*

[3] Brereton M. Cannon D. Mabogunje A. and Liefer L.J. Collaboration in design teams: How social interaction shapes the product. *Analysing Design Activity*, Ed. Cross N. Christiaans H. and Dorst K. pp 319-341. (John Wiley & Sons)

[4] Larsson A. Torlind P. Karlsson L. Mabogunje A. Leifer L. Larsson T. and Elfstrom B-O. Distributed Team Innovation- A framework for distributed product development. In *International Conference on Engineering Design, ICED '03.*

[5] Frankenberger E. and Badke-Schaub P. Information management in engineering design – empirical results from investigations in industry. In *International Conference on Engineering Design, ICED '99,* Munich, August 1999. (Technische Universität München, Garching)

[6] Eckert C.M. Clarkson P.J. and Stacey M.K. Information flow in engineering companies – problems and their causes. In *International Conference on Engineering Design, ICED '01,* Glasgow, August 2001, pp. *43-50.* (Professional Engineering Publishing, Bury St Edmunds).

[7] Cross N. Teamwork in design: empirical observations of group activity. In *International Conference on Engineering Design, ICED '95, Vol.2,* pp.737-742.

[8] Whittaker S. Swanson J. Kucan J. and Sidner C. Telenotes: Managing lightweight interactions in the desktop, *ACM Transactions on computer-human integration,* 4(2), 1997, pp. 137-168.

[9] Enestrom P. Ritzen S. Nornell M. Co-operation between supplier – buyer in integrated product development: A pilot study. In *International Conference on Engineering Design, ICED '97.Vol.2,* pp.121-124.

[10] Nakakoji K. Fischer G. and Ostwald J. Supporting Asynchronous Collaboration in Evolutionary Design with Representations of Context and Intent. *Designing Communication and Collaboration Support Systems.* Ed. Matsushita Y. 1999. (Gordon and Breach Science publishers)

[11] Beyer N. and Weber F. Concepts and prototype for a practical communication environment for supporting and managing concurrent product development. In *International Conference on Engineering Design, ICED '99,* pp.1431-1436.

[12] Wu Z. and Duffy A.H.B. Using situation thoery to model information flow in design. In *International Conference on Engineering Design, ICED '01,* pp.155-162.

[13] Minneman S. The social construction of a technical reality: Empirical studies of group engineering design practice. *Ph.D. Thesis,* Department of Mechanical Engineering, Stanford University.

[14] Trousse B. and Christiaans H. Design as a discursive activity. In *International Conference on Engineering Design, ICED '95, Vol.2,* pp.436-443.

[15] Christiaans H. Designer's knowledge base and structure: An analysis of argumentation in design. In *International Conference on Engineering Design, ICED '99,* pp.977-982.

[16] Senge P. *The fifth discipline: The art and practice of the learning organization.* 1990. (Currency Doubleday, New York)

[17] MacGregor S. P. Thomson A. I. Juster N. P. A multi-level process based investigation of distributed design. In *Proceedings of the Engineering Design Conference,* EDC '02, Kings College London, England, July 2002.

[18] Schon D.A. *The reflective practitioner: How professionals think in action*, 1983. (Basic books Inc)

[19] Kleinsmann M. and Valkenburg R. Barriers to shared understanding in collaborative design projects. In *International Conference on Engineering Design, ICED '03.*

[20] Eppinger S.D. and Salminen V.K. Patterns of product development interactions. In *International Conference on Engineering Design, ICED '01, Vol. 1,* Glasgow, August 2001,

pp.283-290 (Professional Engineering Publishing, Bury St Edmunds).
[21] Eckert C. and Stacey M. Dimensions of communications in design. In *International Conference on Engineering Design, ICED '01*.
[22] Stacey M. and Eckert C. Managing Uncertainty in design communication. In *International Conference on Engineering Design, ICED '01*, pp.441-448.
[23] Chiu M. An organizational view of design communication in design collaboration. *Design studies*, 23(2), 2002, pp.187-210.
[24] Thoban K. and Weber F. Designing information and communication structures for concurrent structures for concurrent engineering – findings from the application of formal method. In *International Conference on Engineering Design, ICED '99*, pp.989-994.
[25] Harvey C.M. and Koubek R.J. Towards a Model of Distributed Engineering Collaboration. *Computers in industrial engineering*, 35(1-2), 1998, pp.173-176.
[26] Eris O. Manifestation of Divergent-Convergent Thinking in Question Asking and Decision Making Processes of Design Teams: A Performance Dimension. In *Human Behavior in Design*, Ed. Lindemann U. pp. 142-153, 2003. (Springer- Verlag, London)
[27] Ahmed S. Understanding the Use and Reuse of Experience in Engineering Design. *Ph.D. thesis*, Cambridge University, Engineering Department, December 2000.
[28] Lehnert W.G. *The process of question answering: A computer simulation of cognition*, 1978. (Lawrence Erlbaum Associates, New Jersey)
[29] Bales R.F. *Interaction process analysis: A method for the study of small groups*, 1951. (Addison-Wesley Press Inc)
[30] Tang J.C. Listing, Drawing, and Gesturing in Design: A study of the use of shared workspaces by design teams, *Ph.D. Thesis*, Department of Mechanical Engineering, Stanford University.
[31] Nidamarthi S. Understanding and Supporting requirement satisfaction in the design process. *Ph.D. Thesis*, Department of Engineering, University of Cambridge.

Contact: Prof. Amaresh Chakrabarti
Indian Institute of Science
Innovation Design Study and Sustainability Laboratory
Centre for Product Design and Manufacturing
Bangalore – 560012, India
+91-080-22932922
ac123@cpdm.iisc.ernet.in
http://cpdm.iisc.ernet.in/people/ac/ac.htm