Classification for Communication and Communication for Classification In Engineering Design

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I. Introduction

We take the view that engineering design is a reflective conversation (Schon 1998) that includes all that matters in design -- people, sites, materials, drawings, models, products, and practices. These conversations are both made possible and are constrained by various economies of information creation, transmission and maintenance, by tradeoffs of remembering and forgetting and by calculations of cost and benefit, all situated in social-technical contexts.

By being embodied in reflective conversation, design rationality is bounded in both a psychological or computational sense and in a sociological or cultural sense. Design rationality is bounded not only insofar as the interlocutors in a design conversation are limited by computationally tractable economic tradeoffs (Simon 1997) but also because designs are constructed in the social-technical infrastructures and networks (Bowker & Star 1999) where reflective conversations take place. This is why communicating information economically (through classifications for example) operates at both psychological and social levels (Ranganathan, 1959).

Classification has been the primary instrument for achieving economies of information in various communities of practice. However, design accommodates multiple changing individual and collective perspectives by reconciling different classifications of artifacts, processes, and roles. Each community of practice implicated in design work brings to bear its own classifications each of which is an evolving product of tradeoffs and negotiations that in turn are deconstructed and reconstructed in heterogeneous design contexts.

How design engineers approach the interplay of design and classification in the context of multiple perspectives is the main theme of the discussion that follows. Our hypothesis

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is that engineers, in working within actual design situations (with their multiplicity of changing perspectives,
constraints and demands), must create, transmit and maintain quite complex practical classifications to achieve quality, minimize failures and improve operational efficiency. These classifications are often viewed as changeable, prototypical and non-hierarchical. While this allows for flexible and economical structuring of information, it also makes for problems in understanding, maintaining and transmitting at least partially implicit and heterogeneous structures. We will summarize a few empirical studies that illustrate how engineers in collaborative situations handle the tradeoffs between flexibility and economy of classification structures on the one hand and problems of tacitness and heterogeneity on the other. We will also show that when such classifications are not maintained the potential secondary costs are quite large. We end with a discussion of research issues in classification for CSCW.

II. Classification for and in design communication

Simon in his essay, "architecture of complexity," (Simon 1981) points out that hierarchical decomposition is one of the primary means of reducing complexity. We agree that engineering design decomposition of various kinds pervade engineering work, though we would maintain that decompositions do not have to be hierarchical but in practice typically take on the more flexible form of a network. Engineering decompositions can be applied to goals, objectives, constraints and tests, product ranges and variations, functions, task assemblies, technologies, failure modes and so on. These decompositions both depend on but are also the source of further articulation or classification work.

In engineering, classification is driven by the purpose and scope of the information synthesis needed for productive communication. However, the resulting classifications need to combine heterogeneous regulatory, industry, firm, division and domain specific structures that need to accord with one another. For example, functional decomposition of a product affects task decomposition and mismatch between function and task decompositions can lead to disastrous results.

Designers in making the classifications embedded in functional decompositions, part hierarchies, assembly hierarchies, parts catalogs, design catalogs, morphological charts and handbooks accord with one another do not use strict hierarchical structures but often use networks of prototypes or exemplars (Demaid and Zucker ...). Even when engineers establish formal bodies to build standards and institutionalized classification systems, the categories agreed to do not adhere to strict hierarchical relationships and where membership is defined by necessary and sufficient conditions (e.g., material classification

Sargent & Sub ...). Many design projects, especially when it comes to sharing classifications across disciplinary and organizational boundaries are even less bound strict rules of hierarchy and membership. Engineers do not have the time to learn the ins and outs of the classifications of their colleagues. They need to be aided in the classification decision process by being providing with exemplars that encode discrimination criteria. Design practice is always a learning process where complementary communities of practice in the design process are legitimate peripheral participants with respect to one another (Lave and Wenger).

Multiple perspectives, each with their own indigenous classifications, need to be reconciled in the design of complex systems. Classification is based on the iterative development and use of abstract objects and prototypes that have multiple, ambiguous or even no clear hierarchical relationships and determine classes whose members only have family resemblances to one or more prototypes. Design objects are typically proto-types that may be models for future product lines, a stage in the development of an artifact that might become a model for a product line or the coup de grâce of a failed design approach.

In working to create design objects that accommodate multiple perspectives, designers create classification fragments, prototype "classifications" or networks of prototypes rather than non-overlapping, hierarchical classifications. The latter would be too costly to maintain and would be too unwieldy to modify when change occurs, as it always does in design projects.

There is also another dimension of complexity in the use of classifications in engineering design. The evolution of a design not only involves the interweaving of multiple disciplinary classifications but also different classifications with respect to multiple alternative designs. Each design object can fit into multiple design complexes that represent different approaches to a design. These different design complexes can conflict with one another and represent multiple possible design paths. Design closure is reached pragmatically using a prototyping process governed by well channeled, coordinated and timely conversations. Alternative design complexes require different ways of aligning and adapting processes, resources, and contingencies. Each alignment corresponds to a different set of interdependent negotiated promises. Abstract design objects or prototypes go hand-in-hand with the process of design prototyping (Bucciarelli 1997).

III. Design examples

A. Classification breakdown due to lack of formality causing loss of production control

This is a case study on design of electric power equipment used for managing the stable operation of electric power transmission and distribution networks (Subrahmanian et. al., 1995). The study was directed toward information flow characteristics of the design process and its performance. The study was also concerned with the historical evolution of the product including changes in product management that were critical in prototype development.

The product came into existence over 50 years ago. Technical management determined the scope of the product line with customers who were geographically proximal. A product line evolved in responding to the sequence of customers encountered all with quite similar needs. A product produced for a given customer could be negotiated on the basis of the prototypes without having to introduce substantial variation to the product line. Each variation from the prototype could be produced with minimal impact on manufacturing and scheduling.

After some years of operation, the need to expand the market beyond the geographical region led to a change that made the marketing department responsible for determining the scope of the product line based on the markets they thought could be captured. As new markets were entered, variation of specifications of products increased from customer to customer and order to order. As the number of orders and customers increased, the communication patterns and the information flow were now constrained only by the marketing point of view. The technical constraints needed for scheduling resources and manufacturing and were lacking or underspecified at best. The need for classifying and controlling variation was being sacrificed to capturing a larger market.

Variations in product specification became so extensive and diversified that scheduling all the very different manufacturing sequences became unwieldy. Over a 10-year time period, unpredictability of manufacturing times, reduction in reliability and breakdown in prototype classifications resulted in disintegration of the common understanding of the overall product line. Disintegration of classifications resulted in breakdowns in consensus and conflict resolution. Lack of understanding of the products produced by the firm had become so severe that the firm did not know the variety of products in the product line it produced and could not give firm dates to its customers on their delivery.

A simple prototype classification system based on minimal variation that evolved through incremental modifications would not suffice. A much more intensive organization wide reflection was needed to create a mapping of design, marketing and manufacturing each of which relied on multiple classifications that themselves had to be aligned. Aligning prototype classifications consisting of partial hierarchical relationships in several dimensions required a higher-level classification structure. This higher level structure and the classifications contained therein needed to be flexible and tentative in order to accommodate changing external conditions like multiple differing markets and introduction of new technologies and processes.

Eventually, after substantial and sustained production and delivery problems, the variations introduced by expanding markets were addressed organizationally. A special team addressed the scope of variation by aligning prototype classifications that "harmonized" the product line vis-à-vis markets, design and manufacturing. The entire unit was restructured subsequently to switch over to this more harmonized model.

B. Classification breakdown due to lack of understanding and unavailability of other needed classifications

This case is about the design of public transit rail systems (Subrahmanian, Granger, Milliken, 1999). We discuss how a radical change in organization structure disrupts the shared understanding of the prototypes that served the negotiation and consensus process. Second order costs of this disruption can be traced to the need for rework, redesign and, retrofit of parts and systems after design release.

In particular, what constituted common understanding between the design engineer and the drafting and manufacturing department needed to change to accord with the organizational change, but the support structure required to accommodate did not change. The interfaces and the protocols characterizing the interfaces were not changed, resulting in mismatch of the shared understanding of the needed prototypes classifications and untold problems in the manufacturing and delivery processes.

The first installation of the product occurred 30 years ago. At this time, the product was novel and technologically advanced. As more orders were obtained, the need to manage the variations on the design became very critical to the organization. In order to manage the variations, the transit division borrowed systematic classification procedures for engineering change orders from another division and introduced them into the transit division. Here a new need arose for classifying change that would support the management of design variants. Managing these variants needed a viable process for controlling them across multiple project contexts and multiple objectives such as addressing customer requests and lowering manufacturability and maintenance costs.

With the introduction of the new procedures, the design engineer only worried about the part he was changing for the current project. The designer depended on the manufacturing information department to reconcile the differences between the changed part design and the consequences of that change. The design engineer worked with the specifications of the order in front of him, while the manufacturing information department used product family prototypes to maintain minimum variation. This allowed the manufacturing department to concentrate on production incorporating the new part that was designed by the design engineer into the relevant prototype. When the organization changed and led to the abolishment of the manufacturing information department, the design engineer, in order to change a particular part, now had to maintain several different prototypical structures. Minimally, he had to maintain his project part structure. In addition, he needed to efficient access to several types of networks of heterogeneous classifications such as drawing hierarchy, assembly hierarchy and so on. Moreover, he has to negotiate with manufacturing and other similar programs that are executing and maintaining parallel orders. The scope of the interface between the designer, drafting and manufacturing engineers radically changed the amount of information that needed to be processed by the design engineer leading to cognitive overload and rework. What is needed is to help the design engineer evaluate the class and consequence of his changes to the classification network governing both projects and designs

IV. Understanding classification in design: reflecting on practice and practicing reflection

Engineers engage in reflection as they work. To an even greater extent, designers engage in reflection while they design. Schon calls this reflection in action (Schon & Bennett 1996) and describes how it works when, for example, talented jazz musicians improvise together as they listen to one another and to themselves. Within the structure of a piece and a familiar harmonic scheme, they think, or feel, what they are doing. The piece they are playing is a conversation between them, their instruments, the environment they are playing in and their audience. The piece is continually created as they listen and respond to surprises in the conversation.

Schon distinguishes two other kinds of design reflection. There is reflection on action where the designers pause and think back over what they have done in a project, exploring the understanding they have brought to the case taking stock of unforeseen contingencies and new opportunities. This sort of reflection may lead to a new theory of the case, a reframing of the problematic design situation (both means and ends) that needs to be negotiated and reconciled by all those implicated in the design. In case A above, when the marketing people took charge of the product and the market became global, the necessary infrastructure for organizational reflection in action and conversation was not in place. This could only be remedied by the third kind of reflection.

The third kind of reflection is reflection on practice. Designers, again in conversation with others, present or not, may surface and criticize, or at least formulate more clearly, tacit understandings that have grown up around repetitive experiences of designing. This may, in part, be suggested (rationally or hypnotically - Borch-Jackobsen 1997) through contact with other disciplines, though significantly modified when combined with ongoing design reflections and conversations. For example, prototypes in psychology (Rosch 1978) and linguistics (Lakoff 1987) are seen as best exemplars when functioning as classification instruments. As used by designers, prototypes are ambiguous, sometimes abstract and sometimes concrete, potentially belong to a number of type hierarchies or perhaps none. Design prototypes are caught up in multiple economic and computational tradeoffs (Simon 1957) as well as moral and political negotiations. These negotiations are often rendered invisible once a classification becomes established (Bowker and Star 1999). In case B, even though the formal classifications were introduced early, the organizational group that mediated the conversation between design and manufacturing was no longer available. It was forgotten that this group was the lynch pin of the classification infrastructure. Instead of a small group of people maintaining the classification schemes, each engineer had to bear the cognitive load of maintaining his or her own classification. Further the dispersion of classifications and interpretations lead to inconsistencies and errors. The implication is that even when reflection of the third kind takes place, the necessary infrastructure to implement it must be created and maintained. Moreover, this infrastructure has to change to accommodate new participants in the conversation.

Most engineers and even some designers may not view themselves as reflective practitioners, but they operate as if they do; that is, the reflective practitioner is our rational reconstruction of how engineering designers work rather than a normative or prescriptive description of how they should work.

While reflective practice is, in essence, rational reconstruction, the design engineer, to be successful, treats the results of such reflection tentatively rather than elevating it to some rigid, objective, and absolute truth/theorem/theory. Furthermore, the very process of reflective practice is not explicit, formally taught, nor fixed but is, rather, mimetic, "glory based" and transmitted through apprenticeship (Lave and Wenger 1991).

V. Summary and Implications for CSCW

Summarizing our evidence and arguments, communication for design classification is reflection in practice whose objective is economy of information exchange where economy is defined to cover the generation, transmission, and maintenance of information. In reverse, classification for design communication is reflection in and on action driven by the need for information economy. Finally, if both do not mutually support or reinforce each other engineering failure is a consequence.

Reflection and resulting classifications address the need to manage the complexity of the task and the multiple interfaces of information exchange. But this need can only be satisfied if the necessary collective space and time for reflection are available. Further the classifications must assume some embodied form that is sustainable and accessible.

We have illustrated in our case study that when reflection and classification are not maintained, the result is an unwieldy and uncontrollable design and manufacturing process. This was due to a lack of time for reflection as well as the inability to adequately recognize and control the drift of specifications and design prototypes. At this point only a process of reflection on practice instituted by the organization could alleviate the problems. This process required bringing the parties together to align and harmonize the different views.

In general, the implication for CSCW work is that all three forms of design reflection must be supported. Their differences must be acknowledged. Reflection in action is different from both reflection on action and reflection on practice because the former cannot take place without significantly interrupting the action itself. Reflection on action and reflection on practice can occur after the action so there is more opportunity for reflection. However, reflection on action can occur in an ad hoc and relatively uncoordinated space and time whereas reflection on practice takes commitment and coordination of space and time. While these differences are important to the computer support of collaborative work, they all have in common that embodiment and maintenance of classifications and other information structures are necessary for all three kinds of reflection. Computationally embodied classifications are a shared space for reflection in and on action and on practice. The composition and recomposition of classifications can be improvised in action but also more deliberately restructured at different levels of complexity when there is time.

More specifically, several implications can be drawn for the development of support (computational and other) systems for CSCW in design. First, the systems must support the creation of multiple classifications and allow for their use as prototypes; i.e., allow the creator or the user to modify the prototype, "test" its usefulness, return to a previous state of the prototype, and repeat the cycle with a minimum of effort. Otherwise, the system will either not be used ("shelf-ware") or otherwise discarded (if it were an organizational system, for example).

Furthermore, these prototype classifications must allow for ambiguity in the sense of allowing for arbitrary network-like structures rather than classic hierarchical structure as, for example, imposed by most common computer file systems. In particular, forcing users (designers) to create desired network structures by copying instances (nodes) of information to multiple location, will lead to fracturing the unity of the node as the nodes themselves are modified in the course of the design.

Finally, CSCW systems assisting designers must allow the designer the option of selective discovery. The designers must be provided with the tools to discover, at their own discretion, the changes that are made to existing classifications. This can be done either directly by formal revisions or indirectly by discovering the way terminology is used in various kinds of design and organizational documents.

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