Boundary Objects and Prototypes at the Interfaces of Engineering Design

Eswaran Subrahmanian[1,2], Ira Monarch[1,3], Suresh Konda, Helen Granger[1], Russ Milliken[1,2], Arthur Westerberg[1,2] and the *n*-dim group[1]

[1]Institute for Complex Engineered Systems
Carnegie Mellon University
Pittsburgh, PA 15213

[2]Dept of Chemical Engineering
Carnegie Mellon University
Pittsburgh, PA 15213
sub@ices.cmu.edu

[3]Software Engineering Institute
Carnegie Mellon University
Pittsburgh, PA 15213

Revised and Resubmitted to Special Issue of JCSCW
March 16, 2000

Boundary Objects and Prototypes at the Interfaces of Engineering Design and Manufacturing

Abstract

The primary hypothesis of this paper is that internal and external changes in design and manufacturing organizations affect the viability of boundary objects (representations, drawings, models – virtual and physical) and require changes in the underlying distributed cognitive models. Internal and external factors include new advances in technologies, insights into organizational processes, organizational restructuring and change of market focus. If the above hypothesis is true, then there are consequences for the methodologies of designing computational support systems for co-operative engineering work. We provide evidence by describing three empirical studies of engineering design we have performed in large organizations. We investigate how changing technologies disrupt the common grounds among interfaces and how this has opened a debate on the role of boundary objects, especially in the product visualization and analysis arena. We then argue that changes in market forces and other factors leading to changes in organizational structures often lead to erosion of common understanding of representations and prototypes, above all at the interfaces. We conclude by making the case that every structural and information flow change in engineering organizations is accompanied by the potential deterioration of the common ground. This requires the synthesis of new common grounds to accommodate the needs of new interfaces.

1. Introduction

The primary hypothesis of this paper is that coordination at the interfaces of engineering design activities requires the construction and maintenance of shared representations within and among different perspectives. Further, the need and understanding of these representations are dictated by the organizational structure and information flows characterizing the design process. If the above hypotheses are true, then there are consequences for the methodologies of designing computational support systems for cooperative engineering work. We shall provide evidence to support these hypotheses by drawing from three of our empirical studies of engineering design in transnational manufacturing firms. We argue that changes in organizational structure and information flow as well as changing technologies have serious consequences for organizational performance because of mismatches of shared understanding at the affected interfaces. We conclude by making the case that changes in structure, process and information flow in engineering organizations are accompanied by the potential deterioration of common grounds at the interfaces, thus requiring the creation of new boundary objects and prototypes.

The paper is organized as follows: Section 2 is a brief description of our perspective on the role of boundary objects and prototypes at the interfaces of design and manufacturing. Section 3 summarizes other theoretical threads overlapping with our thesis. Section 4 illustrates the effect that introducing CAD had on engineering drawings as boundary objects and their underlying prototypes. Section 5 describes three case studies showing how the lack of organizational processes and change of organizational focus and structure causes a loss or lack of shared understanding resulting in the inefficacy of boundary objects. Section 6 concludes that a primary source of engineering failures is the breakdown of communication at the interfaces of design and manufacturing. It ends with the proposal that computational power needs to be more effectively utilized and embedded in work processes to support the communicative efficacy of boundary objects.

2. Boundary Objects and Prototypes at the Interfaces

There have been several studies in recent years on the nature of engineering design work. These studies provide an alternative view of engineering as a social construction process reconciling conflicting goals, objectives, tests and the interpretations in the development of the product by participants with perspectives from different object worlds (Bucciarelli, 1994). The product description emerges through the articulation and reconciliation of these factors until a common understanding of the product being designed is reached, even if temporarily, to achieve relative closure. In this conception of design, the intermediate representation of the product and the process of creating the product are records of conflicts and consensus. These records trace the lives of virtual and physical objects in the form of evolving sketches, descriptions and models. These objects inhabit the space of negotiation at the interfaces. In Henderson's terms, "the cascade of sketches ultimately made concrete in the final design representation depends on the mobility, stability and combinability of the representation for extension of the network of participants and information…"(Henderson, 1999).

Bowker and Star in their book, *Sorting Things Out* (1999) introduce the concept of boundary object (see also Star 1989) as one way of managing the tension between divergent viewpoints. Boundary objects capture very well the role of objects that inhabit the space of negotiation at the interfaces and serve to support cooperation between participants without agreement about the classification of objects and actions (296). Yet boundary objects can inhabit several communities of practice and satisfy the information requirements of each of them. This does not mean that use of boundary objects requires that participants need to have a shared understanding to establish coordination. Star and Griesemer (1989) first introduced the concept in studying a museum, where the specimens of dead birds had very different meanings to amateur bird watchers and professional biologists, but 'the same' bird was used by each group. The dead birds allowed the bird watchers and biologists to coordinate their activities even though they had completely different understandings. "Boundary objects arise over time from durable cooperation among communities of practice. They are working arrangements that resolve anomalies of naturalization (at-homeness with categories or objects) without imposing a naturalization of categories from one community or from an outside source of standardization." (297)

In this paper, we introduce a concept related to boundary objects, prototypes, in order to emphasize that in engineering design, it is often important to achieve partial agreements about the classification or at least ordering of objects and actions. Prototypes are not only a static *means* of translation (Bowker and Star 1999, 297) but also dynamically change and rechange their representational status in the achievement and breakdown of shared understanding. In our view, prototypes reconcile at a cognitive level "two or more differently naturalized classification systems" (297) by acting as intermediaries between them enabling two communities to share at a cognitive level the same quasi classification system or concept (term) network. For Star and Bowker, two communities may use the same classification system as a boundary object without necessarily sharing it at a cognitive level. We agree that the two groups do not have to share all, or even most of their respective classifications or systems of ordering. What we want to argue is that some cognitive link between the two systems has to be established even if it is only temporary and evolving. We call the mediators serving as such links prototypes.

We believe prototypes as well as boundary objects play a role at the interfaces of engineering work because in order for boundary objects to be a means of translation, there must be an interpreter (or interpreting system) who (that) links the different perspectives (classifications or ordering principles) to one another and to the boundary object. Insofar as a boundary object becomes a link among one or more organizing systems or networks, it creates a new but tentative organizing system or network. In this sense, a boundary object is also a prototype. The more links the boundary object has to multiple perspectives the more prototypical a role it assumes and the more tentative and fragile it becomes.

Our view is that all boundary objects must play the role of prototypes to a certain extent, though in different contexts and from different perspectives, the cognitive aspects of boundary objects, i.e., what makes them prototypes, may be emphasized or de-emphasized. For example, some people may be dependent on one person in an organization for prototypical understanding underlying the use of a boundary object.

In a study of electric power equipment design, the interface between individual electrical equipment designers and manufacturing was mediated through a single mechanical design engineer (Finger et al., 1993). This mechanical engineer had become a librarian holding, in his personal notebook, his classification of the all the designs over 30 years. He evaluated the electrical engineers' design specifications as boundary objects with respect to his design specification classification (a prototypical cognitive structure). The underlying cognitive structure enabled him to verify the design and finalize a design specification document (boundary object) for drafting and manufacturing.

The existence of this personal classification of design documents that continually flow from the different design engineers through the mechanical engineer to the drafting and manufacturing engineers is evidence of a prototypical cognitive structure unarticulated in the boundary object itself. The interpretation of the design document drives the co-ordination of work between design intent and manufacturing. The underlying classification of these design documents is invisible to the electrical engineers and the manufacturing engineers. In fact, they do not directly impose any classification on these boundary objects in accordance with Bowker and Star's claim. The mechanical engineer who is at the crossroads of information flows between the two groups has provided a scaffolding for these boundary objects in cognitive structures he has constructed, thus providing a cognitive link. This cognitive structure is usable only by him to allow him to be able to reconcile differences between design (electrical and mechanical) and manufacturing in the particular design specification in question. Retirement of this engineer, the sole interpreter and translator, was about to make this company lose this cognitive link to the boundary object. We shall illustrate this link further in the case studies section.

We use of the word prototype in this paper is to signify cognitive structures -- verbal, gestural and virtual representations and models, protocols, process graphs, physical artifacts -- that serve as partial or complete representation(s) and/or classification(s) of the “contractual” descriptions of the product or the process by which it is produced. The reason for choosing this interpretation of the term “prototype” is based on the following assumptions. Design of a product can be viewed as a series of temporary closures on the inter-related structural, functional and behavioral specifications of the artifact and its design and production processes. These closures are inherently malleable so as to allow for the continuous revision of the “theory” of a product and its production. However, this “theory” is subject to revision due to a number of external and internal factors. Hence, the role and status of boundary objects and prototypes at the interfaces grasped in the “theory” of the design are extremely fragile. It requires constant attention to its sustenance and re-constitution from the constant shocks to which it is subjected. Most often in current day organizations there is a lack of processes to sustain the fidelity and usefulness of this “theory”. Our essential hypothesis in this paper is that, any factors producing changes in how multiple perspectives are handled, including market changes, organizational restructuring and introduction of new technology, can result in breakdown of prototypical understanding supporting the use of boundary objects and their effectiveness. This understanding is critical to the support of CSCW systems.

3. Supporting Theoretical Threads

Before proceeding to illustrate our hypothesis through use of cases, we will touch on other theoretical threads that lend credence to our hypothesis. They are a) design as theory building activity, b) use of language for joint action and c) mechanisms of interaction in CSCW. We provide a brief summary, as a complete exposition of these issues has to be done in a separate paper.

- Design as theory building: Reddy et al. (1997) and Naur (1985,1992) have argued that design is a process that is very akin to the theory building process. In fact, they contend that designing is artifact theory building where designers create representations (read prototypes) that reflect their current understanding of the product. The collections of prototypes and their maturity determines whether they form loosely codified or formally structured languages -- in the form of drawings, various graphical notations, mathematical formulations etc. -- that constitute a theory of the artifact. They base their observations on empirical studies of product evolution and programming. The observation from these studies is that artifact theory is context and group specific and is distributed and informal. While, this view is not expressed in terms of boundary objects and prototypes, the explicit and tacit cognitive structures behind the boundary objects provide “the theory of the artifact”. The more the theory can be made explicit, the more it can be transferred across groups and time and the more flexibly it can be adapted to changing conditions.

- Use of language as joint action: Herbert Clark (1996) has made a strong case for his hypothesis that we operate in different linguistic worlds simultaneously and that these linguistic worlds define the common ground for joint action. For example, the common ground between a father and child allows the father to mention the word "truck" to use the fact that his son is scared of trucks to discipline him. The language between the father and son is facilitated by the common ground between them. Clark (1996) further argues that language is the medium of joint action, and the common ground determines how well the joint action can be accomplished. Where joint action is required, lack of common ground would lead to efforts directed at creating this common ground. While these observations are for use of language, and therefore words, we contend that it is no different when they are visual or physical representations. In both cases the common ground is critical in the process of joint action. We contend that the common ground is embodied in the languages, representations and materials describing the prototypes. When there are no prototypes to serve the interfaces, we believe "pidgin"-like sub-languages emerge between the interfaces and then they subsequently become systematized as prototypes for use as common ground beyond its inventors (Monarch, et al., 1996, Davis et. al., 1999). In empirical studies of multi-group student software projects, Dutoit et al. (1996) found that groups that reconciled their terminology earlier in the design process managed to finish their work on time. The studies have shown that introducing an issue based method of recording meetings to facilitate the communication process, improved the quality and complexity of software produced in the same time frame. The scope and extent of articulation of the common ground needed to perform joint action determines the efficacy of the process. Liefer and Mabogunje (1996) have observed that product design group performance is related to the number of terms generated during the process. They found that groups with fewer numbers of terms in the vocabulary they created for the project performed less well than others with higher numbers of terms. If one were to follow Clark's hypothesis, then the group with higher number of terms achieved better common ground, resulting in better performance. In Clark’s terms, the common ground is not expressed in terms of boundary objects or prototypes but in the sense of contextual common understanding of terms as necessary for joint action. His purpose is not to discover the underlying cognitive structures but the use of language in joint action. We believe that Clark’s and Lakoff’s views are complementary. Using Lakoff’s notion of cognitive model against which prototypes and boundary objects can be understood, Clark’s common grounds can be elaborated in Lakoff’s models and prototypes (Lakoff, 1988).

- Design as CSCW: CSCW has been searching for its theoretical roots from its inception (Bannon and Schmidt, 1993). Strauss, from a sociological perspective, and recently Herbert Clark, from a linguistic perspective, are serving as theoretical touchstones for a number of research groups (Strauss and Corbin, 1994; Clark, 1996). The notion of "boundary objects" suggested by Star as the object of mediation growing out of Strauss' work has been a very significant influence (Star, 1989). Schmidt and Simone introduce objects of mediation as mechanisms of interactions that serve as "artifacts/protocols" of co-operative work (Schmidt and Simone, 1996). From our perspective, artifacts, protocols, languages, classifications, and representations are boundary objects requiring prototypes that serve the purpose of building the process and product theories in the course of engineering design. We agree with them that these symbolic and other types of protocols are boundary objects that address co-operative work defined as articulation work. However, the cognitive inter-relationships embedded in the cognitive ordering of these boundary objects are not of direct interest to them. In engineering design, product structure, product variety and other factors directly affect the organizational structure and the status of the boundary objects at the interfaces, often needing a translator of the boundary object using and maintaining the cognitive structures underlying the boundary objects.

In the next section we describe how technology has affected one such boundary object – engineering drawings. With this example as a starting point, we present several case studies to examine what happens to the effectiveness of the boundary objects in the design process. The cases examined include change in the participants who support the use of the cognitive structures and change in the organizational structure or driving force.

4. Engineering Drawing: The impact of technology on the creation of engineering drawings -- the virtual visual prototype

The use of engineering drawing and visual representations as boundary objects that function at the interfaces to support and be supported by common understanding and coordinate work has been well documented from empirical studies (Henderson, 1999). Henderson goes further in arguing that use of such visual languages rely on the explicit reading of the drawing as a visual syntactic script (boundary object) with its semantics (prototypes) requiring the tacit understanding of the contexts of use by participants. In the book *Engineering and the Minds Eye*, Ferguson argues that drawings are the primary mode of communication between designers and manufacturers of products (Ferguson, 1994). He claims that the rise of the engineer from the artisan can be linked to introduction of this mediating visual representational language. The use of drawings and use of multiple sources of manufacture for parts was used by Brunellischi 500 years ago so he could be their sole translator/mediator of the boundary objects that supported decentralization of production and kept his competitors from understanding his designs (Ferguson, 1994). The use of drawing and the profession of drawing or drafting have been critical to the rise of engineering since the renaissance.

In the last 30 years, computer aided design (CAD) tools have been introduced in the engineering workplace to replace manual drawings, with the goal of improving productivity. Henderson, in her study of visual representations in design, argues that manual drawing methods had a well-developed language and the tacit understanding among its practitioners to interpret drawings. She then argues that the move to CAD introduced new classes of errors because of the new sets of operations, such as symmetry operators whose semantics were new to the user and not well understood.

Bhavnani and John have corroborated these observations. They found that CAD tools did not improve productivity beyond 5% in the first year. They observed that real productivity growth took place only after 5 years (Bhavnani and John, 1997). Their interpretation was that CAD operators primarily use a cognitive model of manual drawing methods and then interpose computational operators they learn in using CAD tools. Bhavnani and John think that systematic training might reduce the time taken to learn how to use CAD tools.

An interpretation of Bhavnani and John’s work they seem to share is that use of CAD tools requires significant conceptual shifts because of the fundamental extension to manual procedures. These shifts are required because of the CAD tools' capacity to manipulate and compose structures of geometry, things not possible in manual drawing. Clearly this change requires a shift in the cognitive models of drafting and manufacturing engineers. Erroneous drawings/interpretations are clearly possible due to incorrect interpretation of an operation on a structure. An understanding of new vocabulary and models is also critical in enabling negotiation and reconciliation at the interfaces. The primary observation here is that a technological shift in the creation of drawings (boundary objects) has created a conceptual shift with its attendant language and its interpretations, hence changing understanding of these boundary objects through introduction of new prototypes in the use of design tools.

There is evidence of error and failure in mismatches between different cognitive models in the use of CAD tools, especially at their introduction. There are several examples of these mismatches leading to failures in engineering design (Collins, 1997; Petroski, 1994; Ferguson, 1994; Henderson, 1999). It is not our purpose to survey or elaborate them here but to point out that introduction of change at the interfaces can have unintended and costly consequences. In the next section, we present case studies that emphasize the relationship between the structure of information flows and the role of boundary objects and prototypes at the interfaces.

5. Case Studies

In this section we briefly present three empirical case studies to illustrate loss of efficacy of boundary objects and the need for development of new understanding. The studies presented here were done over the last six years. The objective of the empirical studies was to create an understanding of the information handling and management in engineering design firms from several countries. These “information flow” studies were used as a means to design collaborative engineering support systems. Our approach to engineering design support is presented elsewhere (Subrahmanian, et al. 1997). An example of this approach resulting in a collaborative computer support system can be found in (Davis, et al., 2001). In our presentation of the cases, we will be using only fragments of the information flow processes that identify the important interfaces to illustrate our points. The method used in the “information flow studies that result in the information flow maps in Appendix A. In the case studies, fragments or abstractions of the information flow maps are presented for exposition.

Case I: Erosion of the fidelity of boundary objects and prototypes at the interfaces due to uncoordinated information flow

This is a case study of the design of a two classes of transformers in an electric power equipment company. Part of the focus of the study was on intra-project and inter-project information needs and information flows (Finger et. al., 1993, 1995). In this exposition we will take project-based information flows of boundary objects at the interfaces. Figure 1 provides the boundary objects exchanged and the actors. These actors use and create design and manufacturing specifications. The actors must interpret and translate these boundary objects. In Figure 1, the development engineers and their relationships are shown. These engineers play a role in creating and maintaining cognitive structures (design tools and manuals) that support the interpretation of the boundary objects. This responsibility rested on the development department for both the transformer designs. We will see the performance of similar boundary objects is dramatically different in each case.

In the example we examine the use of analytical tools (a computer model) and the design manual (a words and drawings model) in the design of the artifact. Both of these models embody the cognitive structures that have been generated over time about the artifact. They are a record of reconciliation between the engineers, designers of the programs and manufacturing personnel serving as a "theory" of the artifact. This theory of the artifact is what Schmidt and Simone's would call the field of work. The field of work delimits what we are calling the cognitive structures or prototypes that underlie the use of the symbolic structures that mediate work. Schmidt and Simone think of these mechanisms of interaction as boundary objects. The common grounds (Clark, 1996) of the field of work are critical to the functioning of boundary objects. The viability of the common grounds in the field of work determines the effectiveness of the understanding and interpretation of boundary objects by the different parties. On our view this understanding is tacit and subject to change whether for internal or external reasons. The engineers, designers and manufacturing people who handle the same boundary objects require some mediating understanding that connects the boundary object to the cognitive models of each. However, these intermediary concepts are neither explicit nor even part of a well-defined semantic structure that can be rationally reconstructed on the basis of the successful handling of the boundary objects. It is in this sense that these intermediaries are prototypes. Because they cannot be reconstructed as a semantic network does not mean they do not exist.

Figure 1 goes here

Figure 1. Erosion of prototypes and boundary objects due to breakdown in information flows

Our observation and study of two transformer design processes (call them A and B) in the same company showed that the efficacy of analytical tools and design manual were poor in one of the transformer design processes (A) in contrast to the other (B). The primary measure for their performance difference was the percentage of tests on which a transformer that reached the test floor satisfied its design requirements. On investigating the differences, it was observed that, in the case of poorly performing transformer line A, the use of test data and other performance data to update the analytical tools and the design manuals were as much as two years late. In the case of the second, better performing transformer line B, the analytical tools and the design manual were kept up-to-date by assigning responsibility to a specific engineer to maintain fidelity of the design tools and the design manuals. This engineer provided the mediating understanding for the different perspectives.

This person visited the manufacturing facility and the test facility everyday to collect data on designs that were sent to them. He used data to classify, verify and modify the underlying distributed cognitive model of the artifact represented by the design tools and in the design rules in the manual. His efforts to keep the analytical tools and manuals used in the production and use of boundary objects in sync with the underlying prototypes yielded approximately a 98% success in design to test. The test success rate for case A was only about 60%. The reason for the poor performance in case A was that the developers of the computational tools and the design manual were not provided with test information and other failure information. They did not actively gather this information and they were not performing the role required to maintain fidelity of the boundary objects with the field of work. The individual engineers received information only on the designs they were responsible for. They often made adjustments to the results from the tools and created ad hoc rules based on a limited classification of their designs. This fragmentation and lack of systematic translation of cognitive structures of the different product perspectives led to a deviation in the understanding of the boundary objects. This lead to costly rework sometimes even after the devices were shipped.

Case II: Change in the driving force in product management leading to erosion of shared prototypes mediating the boundary objects

This case study is based on the study of design processes of electric power equipment used for managing stable operation of electric power transmission and distribution networks (Subrahmanian, et. al, 1995). The design and manufacture was in a single geographical location. The study was directed at the performance and information flow characteristics of current design and manufacturing processes, as they existed. However, the historical evolution of the product and changes in product management were critical in the erosion and subsequent reconstruction of boundary objects in the development of the product. The product came into existence a few decades ago. Technical management determined the scope of the product line with customers who were geographically proximal. The company had a stable product line with appropriate manual procedures for design and production. The number of product variations was small and interpretations of the boundary objects were well controlled.

After some years of operation, the need to expand the market beyond the geographical region led to a change that left the marketing department to determine the scope of the product based on the market they could capture. As they entered new markets, the specifications on the device started to vary from customer to customer and order to order. The number of orders and customers increased, but the communication patterns and the boundary objects that constrained the design from a technical point of view were now dominated by the marketing point of view. At this juncture, the boundary objects were starting to be interpreted with more difficulty, often requiring several phone calls and other informal modes of interaction. This led to unpredictability of the manufacturing processes needed to satisfy a customer delivery. The new extensions to the design and changes in manufacturing that resulted were not coordinated with marketing. In fact, the latter was continually changing specifications (Figure 2). The consequences of this change took several years to become manifest. Many of the conversations and agreements were never recorded or monitored, resulting in the breakdown in the ability to translate and manage the boundary objects. Organizational changes and power relationships also played a role in the erosion of the effective use of boundary objects and the breakdown of information flows. In this case, mediating understanding was lacking. The old understanding no longer worked. New prototypes that needed to be developed were not developed, at least for a time.

Figure 2 goes here

Figure 2. Change of driving forces in product design and loss of understanding

The inability to translate customer requirements for a product had become so pronounced that the firm could not give firm dates to its customers for delivery. This led the company to institute a concurrent design process by which they "harmonized" the product line with design, marketing, and manufacturing. The idea of harmonization was to create a product line with its attendant tools, manuals and cognitive models that would be understood by the marketing, design, and manufacturing professionals and would cover 90% of the market. The product was redesigned to create a modular functional architecture that was configurable with clear interfaces to address the needs of the chosen markets. Based on this harmonization process the boundary objects were re-designed to accommodate the new architecture of the product line. The interesting aspect of this case is that the original boundary objects had failed to control the variations resulting in inefficiencies. Creating new boundary objects and cognitive structures that reconciled the translations and interpretations of the boundary objects between the different perspectives in the new operating context was the only way to regain control of the process. However these developments did not amount to the replacement of one explicit and well-defined cognitive model with another. The breakdown in understanding resulted in old concepts becoming inapplicable and new ones being inadequate. Ineffective prototypes became the rule and a new design process had to be established in order for new more effective prototypes to evolve.

The primary mode of failure identified in this case results from changes in the market forces that led to the erosion of needed interpretations underlying the use of the boundary objects. This is a classic problem in a number of industries operating globally.

Synthesizing a variety of products is a combinatorial problem that depends on how the firm controls proliferation of interdependent functional, technological and physical/virtual configurations of the product variety (Wren, 1997). The next case illustrates that even with processes for controlling variety, lack of careful attention to the underlying cognitive structures supporting the boundary objects, can lead to inefficiencies.

Case III: Change in the organizational structure and the loss of understanding of the boundary objects.

This case is about the design of public transit rail systems (Subrahmanian, Granger and Milliken, 1999). We show how a radical change in the organization structures alters the status and shared understanding of the boundary objects that serve the negotiation and consensus process. The first installation of the product was 30 years ago when 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 achieve this goal, the transit division borrowed the procedures of managing variations through systematic engineering change orders from another division, and introduced them into the transit division. Figure 3(a) shows the old organizational structure, the boundary objects and the cognitive structures that provide their interpretation. Figure 3(b) shows the current structure and the change in the interface boundary objects. Over the years the company has been merged, bought, restructured and downsized. Each of these changes has affected the company in terms of the level of knowledge, skills, and experience. The new boundary objects shared by the design engineer and manufacturing were a composition of the earlier boundary objects from two separate interfaces: 1) design engineer and manufacturing information department and 2) manufacturing information and manufacturing departments. The re-organization resulted in a new boundary object with additional need for translation between design and manufacturing that did not exist before.

Figure 3(a) and 3(b) go here.

Figure 3. Changes in organizational structure and change of boundary objects at the interfaces

Earlier, the design engineer only worried about the part he was changing for the new order. The manufacturing information department reconciled the difference between the new part design and the consequences of that change to the current and previous projects using the product line. The design engineer worked with the specifications of the order in front of him, while the manufacturing information department used the product family as its prototype to maintain minimum variation. This allowed the manufacturing department to concentrate on production using the new part specification. In the new organization, the design engineer, in order to change a particular part, now had to maintain two boundary objects as one in his negotiation with manufacturing and across similar programs that may be executing parallel orders. The scope of the boundary object composed from the two radically changed the amount of information that needed to be processed by the design engineer. This led to more errors including incompatibility and wastage of parts ordered for different programs.

In this case, the understanding between the design engineer and the drafting and manufacturing department was lost and had to be restructured. The supporting cognitive structures underlying the translations required to accommodate the new engineering change notice form had to be learned by the design engineer. The design engineer Ws required to create, test, replace and test again evolving prototypes.

The failure mode identified in this case is that any structural organizational change will require changes in the characteristics of the boundary objects, a mere re-composition of the existing ECN forms will not suffice. If these boundary objects and their translations at the interfaces are not appropriately redesigned along with organizational change, the consequences are that the firm's efficacy in producing the product both financially and technically is diminished.

6. Conclusion

The creation of new interfaces necessitates serious reexamination of boundary objects and prototypes as part of the common ground. These boundary objects and prototypes evolve and need to be malleable, as they have to address internal contingencies and failures as well as changes due to external forces. The implications of the set of case studies in this paper can thus be far reaching from the perspective of design and restructuring of engineering organizations. If our observations and analyses are valid, the role and status of boundary objects and prototypes in an organization need to be examined carefully and addressed in the design of collaborative systems.

From a Taylorist perspective, economies of scale in production are achieved through relatively static well-defined boundary objects that attempt to minimize the cognitive need of prototypes for effective operation. This model has worked extremely well for mass production where there is little variation. As Taylorism spread and transformed itself around the world, the factors affecting engineering design and production have dramatically changed. Control of design through static and well-defined interfaces to achieve economies of scale has become insufficient. Product variety, technological change, differential production costs by location and market demands have become dynamic. Management of varieties of products is becoming the norm with global operations, causing shocks to the interfaces that were protected by the static top-down model of Taylorist mode of co-operation (The Economist, 2000). Even local operations are not immune to failures when there is lack of attention to the interface structures.

The change from local to global distribution of design and manufacture has increased the number of links that need to be reconciled through the boundary objects and cognitive structures/prototypes that support them. In global operations the underlying complexity makes the interfaces even more fragile than in the past. Further, the structures themselves may have to be made as explicit as possible for managing this complexity. The critical source of failure is in the communicative efficacy of the boundary objects at the interfaces. Engineering can therefore be viewed as design, development and management of boundary objects and prototypes at the interfaces. What needs to be done is to mobilize computational power to support cognitive structuring (prototyping) as an underlying distributed scaffolding, improving the communicative efficacy of boundary objects at the interfaces of design and manufacturing.

7. References

Bhavnani, S.K., and John, B.E. (1997), " From Sufficient to Efficient Usage: An Analysis of Strategic Knowledge," *Proceedings of CHI 97*, 91-98, 1997.

Bannon, L., Schmidt, K (1993), " CSCW: Four Characters in Search of a Context," Readings in groupware and computer- supported cooperative work, assisting human-human collaboration, Baecker, R. M., Morgan Kaufmann Publishers, Inc., 1993

Bucciarelli, L.L. (1994), *Designing Engineers*, MIT Press, 1994.

Collins, M.P.; Vecchio, F.J., Selby, R.J., and Gupta, P. (1997), " Failure of An Offshore Oil Platform Concrete Base," *Concrete Journal*, American Concrete Institute, August 1997.

Clark, H., (1996), *Using Language*, Cambridge University Press, 1996.

Davis, J.G., Subrahmanian, E., Westerberg, A.W. (1999), "Knowledge In a Large Multinational Company," Proceedings of the Carnegie-Bosch Instititute Grantees workshop on Knowledge Management and global information systems, //http:www.cbi.gsia.cmu.edu, Oct, 1999, San Francisco.

Davis, J, G., Subrahmanian, E., Konda, S. L., Granger, H., Collins, M and Westerberg, A. W. (2001), Creating Shared Information Spaces for Collaborative Design, to appear in *Information Systems Frontiers*, August, 2001.

Dutoit, A., "Role of Communication in Software Projects," Ph.D. Thesis, department of Electrical Engineering, Carnegie Mellon University, 1996.

The Economist (2000), "All Yours," March 31, 2000.

Ferguson, E.F. (1994), *Engineering the Mind's Eye*, MIT Press, 1994.

Finger, S., Konda, S.L., and Subrahmanian, E. (1995), "Concurrent Design Happens at the Interfaces," *AIEDAM*, 9, pp. 89-99, 1995.

Finger, S., Gardner, E., and Subrahmanian, E. (1993), "Design Support Systems for Concurrent Engineering: A Case Study in Large Power Transformer Design," *Proc. Int. Conference Engineering Design*, ICED 93, The Hague.

Henderson, K. (1999), *On Line and on Paper: Visual Representations, Visual Culture, and Computer Graphics in Design Engineering*, MIT Press, 1999.

Lackoff, G, Women, *Fire and Dangerous Things: What Categories Reveal about the Mind*, University of Chicago Press, Paper back Edition, 1999.
Leifer, L.J., and Mabogunje, A. (1996), "Measuring the Mechanical Engineering Design Process," FIE 96 Conference, 1996.
http://www.cdr.stanford.edu/~leifer/publications/FIE96/FIE96.html

Monarch, I, Konda, S.L., Levy, S., Reich Y., Subrahmanian, E. and Ulrich, C.(1997), "Mapping Sociotechnical Networks in the Making," Social Science, Technical Systems and Co-operative Work: Beyond the Great Divide, Bowker, G. Star, S. L., Turner, W., Gasser, L. (eds.), Lawrence Erlbaum, 1997.

Naur, P. (1985), "Programming as Theory Building," *Microprocessing and Microprogramming*, 15:253-261, 1985.

Naur, P. (1992), *Computing as a Human Activity*, Addison Wesley, 1992.

Petroski, H. (1994), *Design Paradigms: Errors of Judgement in Engineering*, Cambridge University Press, 1994.

Reddy, J.C., Finger, S., Konda S.L., Subrahmanian, E. (1997), " Designing as Building and Re-using of Artifact Theories: Understanding and Support of Design Knowledge," *Proceedings of the Workshop on Engineering Design Debate*, University of Glasgow, Glasgow, Scotland, 1997.

Schmidt, K., and Simone, C. (1996), Coordination Mechanisms: Towards a Conceptual Foundation of CSCW Systems Design, Consumer Supported Cooperative Work, *The Journal of Collaborative Computing*, Vol 5:2-3, 1996, pp. 155-200.

Star, S.L. (1989), "The Structure of Ill-Structured Solutions: Heterogeneous Problem Solving, Boundary Objects and Distributed Artificial Intelligence," *Distributed Artificial Intelligence*, Huhns and Gasser (editors), Morgan Kaufmann, 1989.

Star, S.L. and Bowker, G. (1999), *Sorting Things Out*, MIT press, 1999.

Strauss, A. and Corbin, J. (1994), Grounded Theory Methodology, *Handbook of Qualitative Research*, Denzin and Lincoln (editors), 1994.

Subrahmanian, E., Daleng, E, and Maeland, A. (1995), Information Flow Analysis of Design at the Power Equipment Division, Confidential Report, 1995.

Subrahmanian, E.; Reich, Y.; Konda, S.; Cunningham, D.; Dutoit, A.; Patrick, R.; and Westerberg, A. (1997), "The *n*-dim Approach to Building Design Support Systems," ASME Design Theory and Methodology Conference, San Diego, September 1997.

Subrahmanian, E., Granger, H., and Milliken, R. (1999), "An Information Flow Analysis of the Engineering Change and Design Specification Process for Transit Systems," Confidential Report, 1999.

Waring, S.P. (1994), *Taylorism Transformed: Scientific Management Since 1945*, University of North Carolina Press, 1994.

Wren, F,H. (1997), "Synthesis of Variety," PhD Thesis, Technical University of Eindhoven, Netherlands, 1997.

Appendix A: Information Flow Analysis

The general focus of ethnographic workplace studies is not requirements generation. These studies attempt to develop descriptions of work situations and artifacts surrounding a particular arrangement of cooperative work. We have adopted a somewhat different approach in our work. Our fundamental premise is that people receive, organize, create, and structure information from a personal and group perspective and are members of different cooperating ensembles concurrently and over time. Each of these cooperating ensembles, whether derived from a project or functional structure, will operate with its own logic of co-ordination and interaction patterns among the participants in a given context. A person caught in this web structure may be part of different sets of co-ordination modes. The information flow analysis focuses on these ensembles and attempts to uncover the different modes of co-ordination and information exchange within and across the ensembles. This approach allows us to focus on important user requirements by identifying the causes and consequences of information flow breakdowns.

Our approach to designing work support systems for collaborative design has been presented in full detail in Subrahmanian et al (1997) and is based on the interactionist perspective on collaborative work. It also draws on some well-documented observations regarding the nature of collaborative design work. Such work environments are rich in the type, number, and information content of interactions among the actors (designers, suppliers, marketing personnel, service personnel, etc.). The nature of the interactions ranges from face-to-face meetings and informal phone and email communications to exchange of formal documents. The number and intensity of the interactions is often dictated by issues such as missing information, lack of access to known information, clarification of terminology, and identification and evaluation of design tradeoffs. Additionally, these interactions are typically structured around specific mechanisms of interaction (boundary objects) such as project schedules, engineering drawings, and test reports. The primary outputs of the information flow analysis are information flow maps for each of the more important cooperating ensembles. These maps can be further analyzed to generate the requirements for a prototype system to support collaborative design work. The information flow analysis is followed by an iterative cycle of prototype system development based on the requirements and the evaluation of the system in the work environment in which it is installed.

The method of data collection employed in conducting the information flow study comprises of a questionnaire survey and follow-up interviews. The questionnaire used for data gathering is in Appendix 1. A free flowing format was used in the interview in order to elicit problems in information exchange and to understand information needs and the characterizations of time-consuming tasks. The interviews were recorded on audiotape. We also used a technique called mind map (Buzan and Buzan, 1993). This is a manual system for recording open-ended interview data that captures both the inter-relationships among the responses to different questions and the temporal connections between described actions. The primary object of the technique is to cluster related ideas and concepts even though they may arise out of sequence during the interview. This enables the placement of each new theme in the most appropriate location, regardless of the order of presentation. It also offers a parsimonious and visually powerful representation of interview data. We used the mind map method as a complement to the linear notes. The two sets of interview data were compared, reconciled, and summarized after each round of interviews.

The data thus gathered was used initially to create information flow maps of the relevant domain. There are two main limitations to this method of creating information flow maps:

1. A study of information flow and use cannot be done outside the workplace of the design and manufacturing organization. The reason for this is that the individuals involved in the design and development process maintain the information for their work in and around their workplace. This allows them to point to and show types and structures of information around them. This aspect is consistent with the approach employed in the workplace studies referred to in the previous section.
2. Not every individual in the design organization was interviewed. The choice of individuals was based on their functional and project roles. An attempt was made to cover as many levels, functional areas, and roles in the organization as possible. In

terms of coverage, achieving breadth was given preference over depth in a functional area. This approach is employed to attain maximum coverage of the information flow along the horizontal or lateral dimension.

In order to ensure the correctness of the information flow maps, they were reviewed and verified by the participants in the study.

Appendix 2: Information Flow Analysis Questionnaire

Which tasks do you perform in relation to the product development process? Give a brief listing.

For each of the tasks; which documents or other information do you need/use? (Ex: specifications, contracts, orders, invoices, procedures, standards etc.)

For each of the above: where/who do you get this information from (Ex: customers, colleagues, other departments, databases, archives etc.)

What format is the information in? (Ex: text/letters, spreadsheets, drawings, photos, database-data, sound recordings, video etc.)

How is the information transferred to you? (Ex: collected, post, fax, email, oral/phone, fileserver etc.)

How do you sort and/or store this information?

What kind of results do you produce? (Ex: different kinds of documents, approvals/controls, physical products etc.)

Who uses the results of your work? (Ex: customer, subcontractor, supplier, colleagues, archives etc.)

How are the results passed on? (Ex: automatically or on request)

Who checks the results/what kind of feedback do you get?

Which tools do you use for your tasks? (Computer assisted and/or manual ones)

Which of your tasks seem most time-consuming or inefficient?

Wishes (tools/new functionalities etc.) or other comments

Figure 1. Erosion of veracity of prototypes due to breakdown in information flows

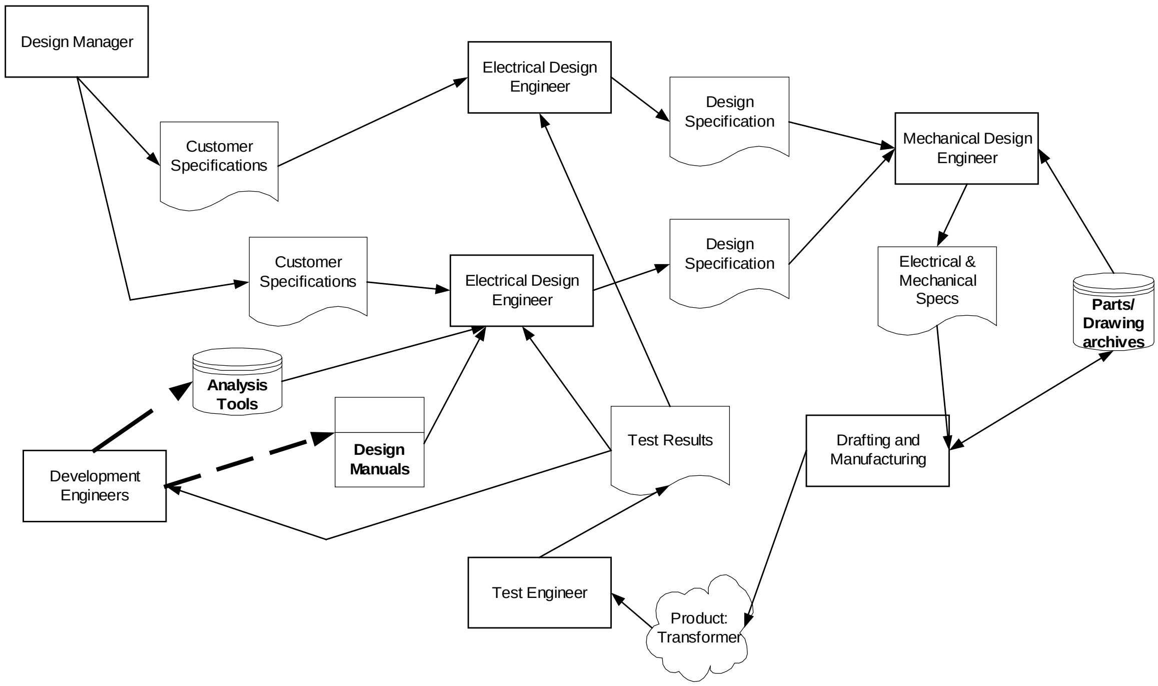
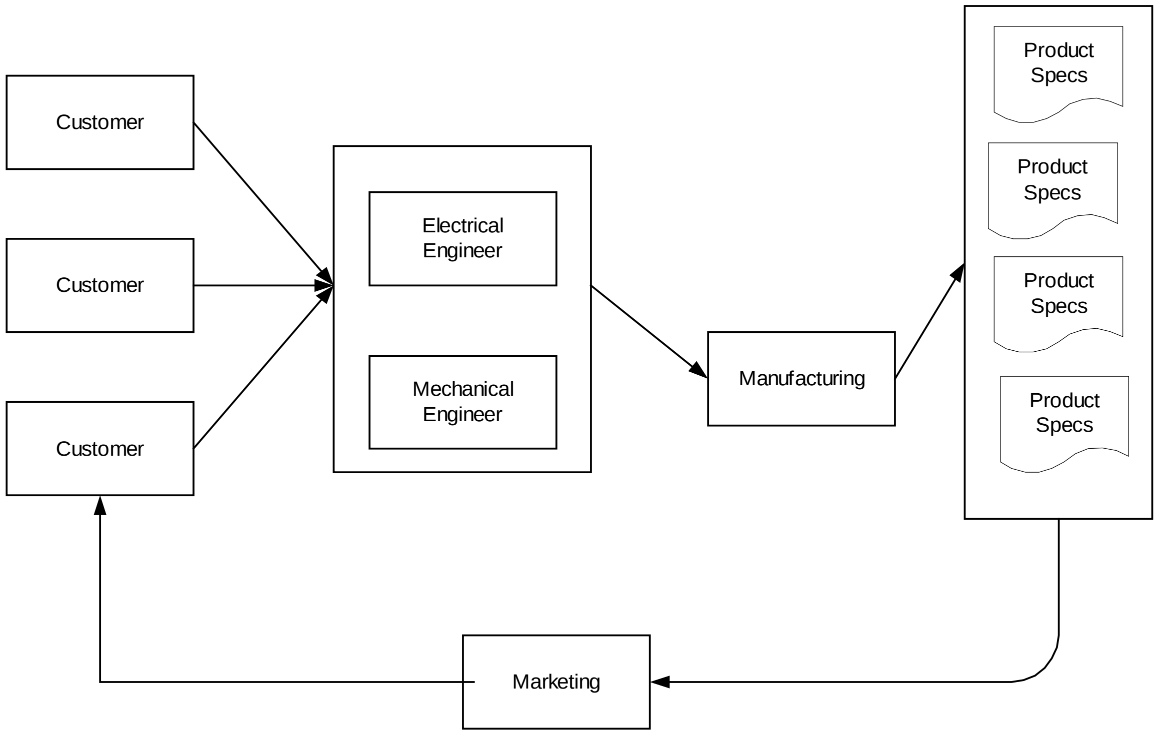
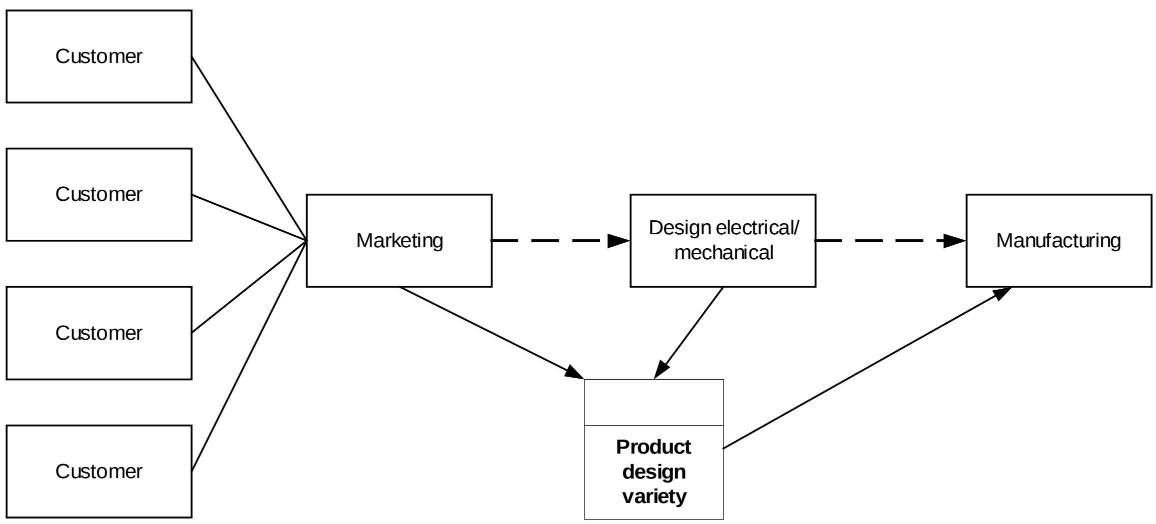


Figure 2. Change driving forces in product design and loss of prototypes

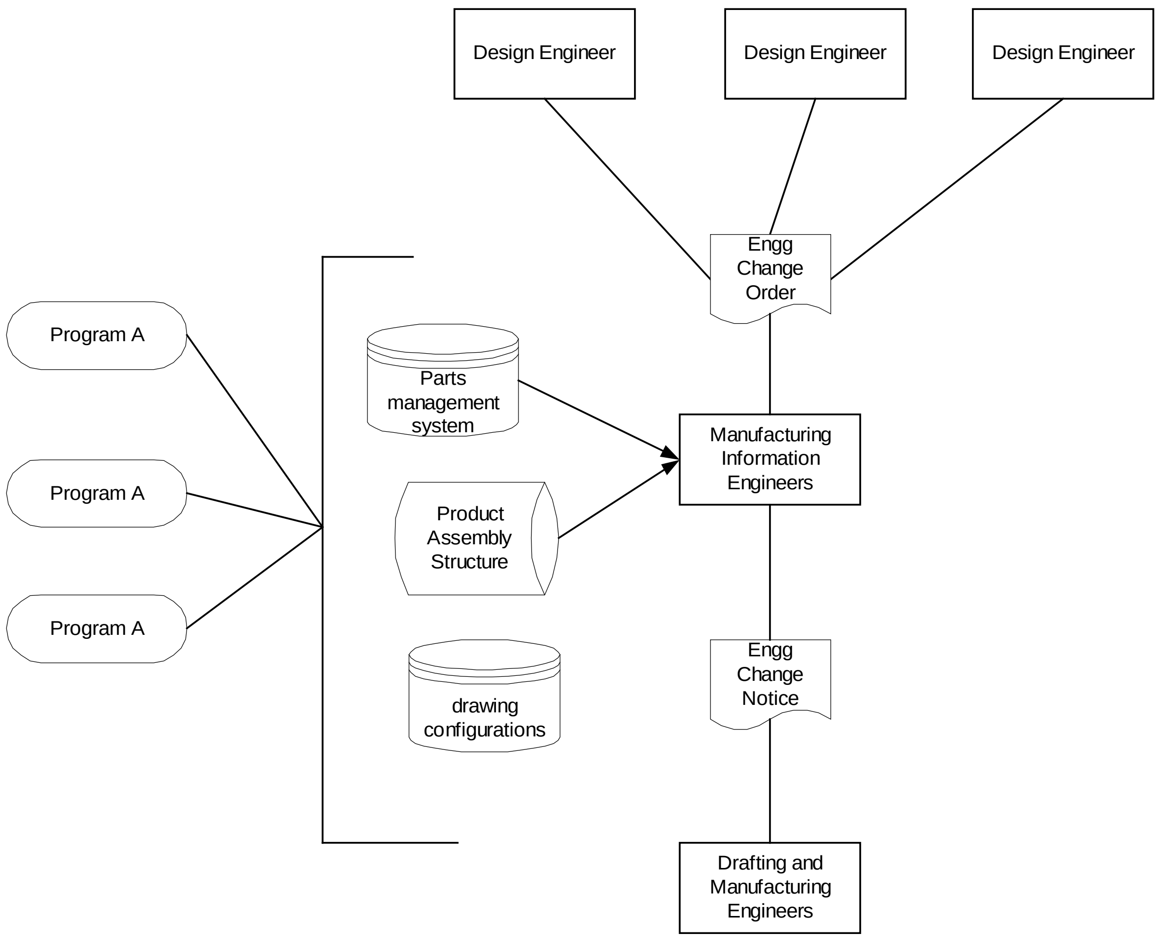


2.a) Structure of the organization with local customers

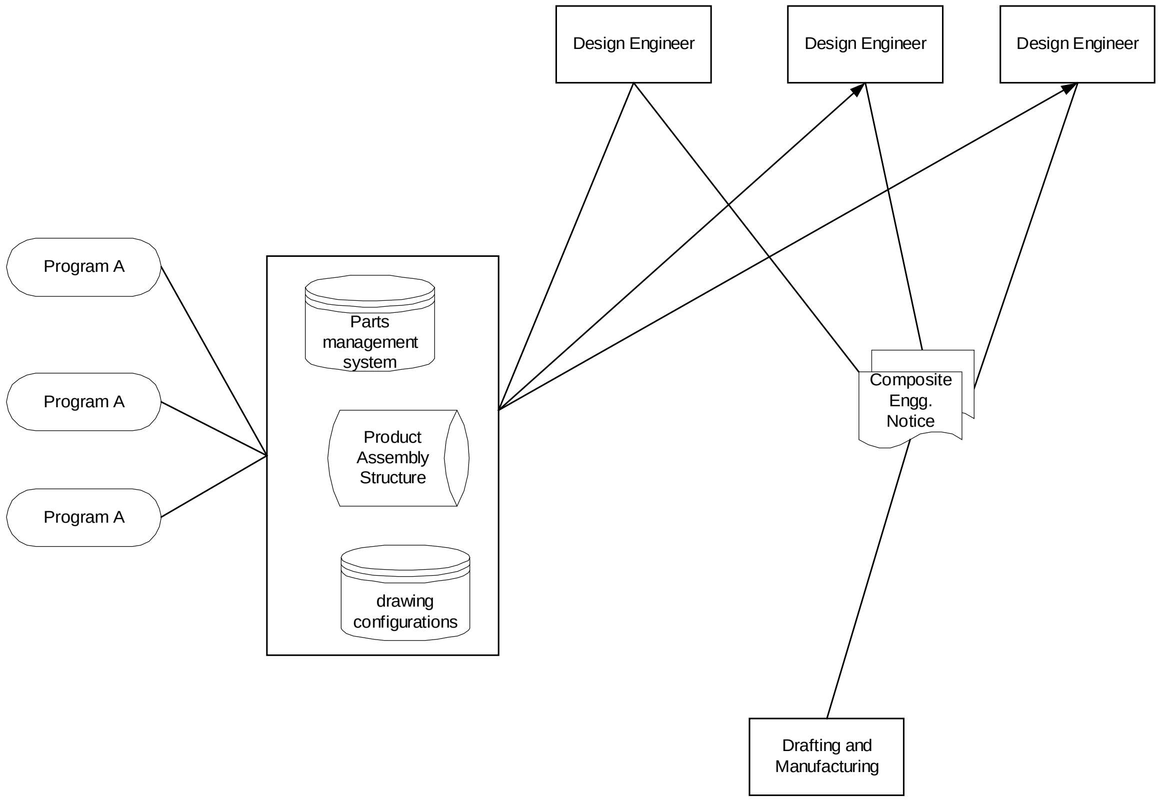


2.b) Change in the driving forces: Marketing

Figure 3. Changes in organizational structure and change of prototypes at the interfaces



3.a) Structure of interactions in 1960-70.



3. b) Structure of the organization in 1990