Proceedings of ICAD2006
4th International Conference on Axiomatic Design
Firenze – June 13-16, 2006
ICAD-2006-01

APPLICATION OF AXIOMATIC DESIGN TO ENGINEERING COLLABORATION AND NEGOTIATION

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ABSTRACT

Engineers and managers who participate in the development of complex engineering systems often collaborate and negotiate. The purpose of collaboration and negotiation is to make correct and best decisions at the various stages of development -- identifying customer needs, establishing functional requirements, and selecting design parameters and process variables – through the collection of best ideas and analysis of the best available inputs. However, there is no assurance that all collaborations and negotiations will lead to better decisions. The quality of collaboration and negotiation is affected by two basic elements: the *system* and the *process* used to promote collaboration and negotiation. A system that promotes positive collaboration and negotiation is necessary to assure that the project has the best information and knowledge available. Systems and processes are also needed to minimize the cost of development, to execute the project on schedule, and to deliver a highly robust, efficient and reliable product. This paper proposes heuristic rules of collaboration and negotiation based on axiomatic design theory and complexity theory.

Keywords: collaboration, negotiation, engineering systems, axiomatic design, complexity

1 INTRODUCTION

Large design projects involve many engineers and managers. They have to work as a team and their work must synchronize to achieve a common purpose. They emphasize concurrent or simultaneous engineering practice, which is to consider all the issues involved in producing a product by bringing in inputs from manufacturing and marketing at the design stage. However, it is well known that a great deal of time is spent among the engineers negotiating their differing opinions and dealing with the interface problems that arises between various groups of the project. The final decision-making is not always done rationally and requires many iterations to correct the mistakes made and to verify the complex decision making process. Furthermore, in the absence of a decision-making framework, collaboration and negotiation among many people may not assure robust and desired outcomes. Hence, industry relies on the DBTF (design-build-test-fix) paradigm, which is costly and unreliable. There are numerous relics of many failed projects.

The DBTF paradigm is not conducive to technological innovation, which is the engine for economic growth. The ability of organizations to innovate partly depends on how well the people within the organization collaborate and/or negotiate. Many industrial companies have instituted organized systems and processes to promote effective collaboration and negotiation, albeit with mixed results. Notwithstanding many of the revolutionary changes brought about by advances in science and technology, human *collaboration* and *interaction* is not yet a fully developed intellectual discipline and thus may constitute an impediment to the innovation process.

The quality of design can determine the functionality, reliability, and robustness of the product as well as the lifecycle cost. The purpose of the collaboration is to enhance the quality of design and development process. To increase the efficiency of operation and the effectiveness of group collaboration, engineering development projects are typically organized one of the following three ways: functional grouping (e.g., control engineering), physical grouping (e.g., power steering, air conditioners), and a matrix organization to capture the good features of both functional and physical groupings. These different organizational structures affect the effectiveness of collaboration among the participants and thus the productivity of the organization. Unless these organizations have the benefit of a theoretical framework for design and project execution, the effectiveness and the productivity of the organization may be compromised.

Collaborative work must be managed well, since the time and effort required to execute an engineering project may increase nonlinearly with the number of participants. The number of engineers, designers and managers required will vary as a function of the nature and the scope of the project. When many people work in a team, they must strive to achieve the common goal of the project. The work must be properly sub-divided, relevant data and facts should not be overlooked, all the contingencies that the project must deal with should be considered, and the workload must be reasonable for the given level of staffing.

Managing a large engineering project may be compared to being a conductor of a major symphony orchestra. In a symphony orchestra, all of the players have musical notes that guide them, and the conductor coordinates and directs the musicians to play the symphony in harmony. Engineering collaboration should be similar to a symphony orchestra. Unfortunately, in engineering, the players (i.e., engineers) often try to collaborate to create the music without the sheet music, and the conductor (i.e., the chief engineer) tries to compose the music without a set of rules, or musical theory.

In this paper, we explore how engineering projects can be executed like a symphony orchestra based on axiomatic design as the framework for engineering collaboration. Some of the ideas described in this paper were also included in the paper submitted to the inaugural issue of the *International Journal of Collaborative Engineering* edited by Professor Stephen Lu of the University of Southern California (Suh, 2006).

METRICS FOR THE ULTIMATE SUCCESS OF COLLABORATION AND NEGOTIATION

One of the fundamental questions on collaboration is: "Why collaborate? Why negotiate?" The answer is obvious and trivial: "To improve the productivity of engineering enterprises and the quality of the products." If we accept these two goals as the reason for collaboration, we must able to measure the effectiveness of collaboration and negotiation among the participants of a project using specific metrics. One may offer the following metrics – which we will call "Improve by an Order of Magnitude Metric (IOM Metric)" -- as examples:

a. Software development – 500 lines of working code per day per programmer (vs 10 to 50 lines / day)
b. Hardware (machines, etc.) – (1/2) time x (1/2) personnel hours x (1/2) cost x (1/2) materials resource
c. Complex system development – (1/2) time x (1/2) personnel hours x (1/2) cost x (1/2) materials resource
d. Quality – 10 times better

BASICS OF COLLABORATION AND NEGOTIATION

In the early stages of a project, a small core of people designs the highest-level system architecture. They are the creator of the central concept at the highest level. The high-level design architecture guide the subsequent development process for the project as the number of participants increase. In the absence of a framework for collaboration, a project can quickly become chaotic with an increase in the number of people. To avoid this problem, the project must be decomposed through a systematic design process.

All participants of a major project should be aware of the goal of the project, the strategy of achieving the goal, and the protocol of collaboration. When a large system is to be designed, there are many issues the designers of engineering systems must deal with and ultimately agree on, such as:

1. Who are our customers?
2. What does the customer need?
3. Of the many possible sets of Functional Requirements (FRs) that can be chosen to meet the customer needs, which FRs should be selected?
4. What are the best means of satisfying the FRs?
5. What should the design be like to make the product robust and reliable?
6. How do we manufacture the products in the most robust, economical and reliable way?
7. How do we test the product to determine its performance?
8. How do we verify the correctness of our decisions?
9. Can the product be successful in the marketplace?

Many decisions must be made to deal with the questions raised above. But how do we know that the decisions are correct or acceptable? Some decisions, regardless who made them, and how many participants were involved in arriving at the decision, may be incorrect or involve the risk of creating unintended results. Basic principles that provide metrics for correctness (or acceptability) must be established, to be sure that correct decisions are made. There are many failures of engineered systems because of wrong decisions made.

ON COLLABORATION SYSTEM AND PROCESS

Effective collaboration and negotiation needs *systems* and *processes* that govern group interactions. The purpose of the system is to organize projects and participants so as to maximize their effectiveness and achieve the goals of the project. The process outlines an algorithm for collaboration and negotiation to reinforce the strengths of all participants, minimize confusion, and deal with the resulting disagreement. Sometimes well-meaning people can disagree because of their misunderstanding of the issues involved, and the lack of fundamental framework for good decision-making. Projects must be organized with a clear idea on how their sub-tasks are related (i.e., uncoupled, decoupled, or coupled). Otherwise, collaboration and negotiation often become chaotic. A system that clearly shows the dependencies among sub-tasks can greatly facilitate communication and coordination and hence improve collaboration and negotiation.

In an ideal situation, both the system and the process for collaboration and negotiation must be designed based on basic principles. To achieve this goal, the system and the process for collaboration and negotiation must be based on design principles that define acceptable designs and provides an overall framework. The system for collaboration may assume many different forms. In this paper, it will be assumed that the system will follow the product-development hierarchy established by the axiomatic design theory. The information flow will be assumed to follow the hierarchical system architecture established by the axiomatic design.

The existence of systems for collaboration and negotiation may not assure success, because the system is a framework that does not provide the contents that go into it to arrive at a right set of goals and solutions. However, a system is necessary to facilitates good decision process. The intellectual content that goes into the systematic framework is discipline specific, and thus requires experts of the subject matter.

The process of collaboration is subject to both rules and protocols. However, in this paper, only rules are presented and the impact of organizational protocol will not be discussed in this paper.

WHY, WHEN AND HOW TO COLLABORATE AND NEGOTIATE – SYSTEMS ASPECT

The need to collaborate and negotiate is determined by three things: complexity of the development project, the financial and other resource commitments required to execute the project, and the need to reduce the risk of the project failing due to the lack of sufficient and necessary inputs to making decisions. These conditions are present when the project size is large, in terms of the number of people and functional requirements that must be satisfied, and when the project is new in terms of the intellectual contents and the objectives to be achieved. A systematic approach such as the one described below is to maximize the probability of success in achieving the ultimate objectives of the project.

Collaborators in engineering projects must understand the design process and the design hierarchy to be able to find the right partners for collaboration and to seek information from the right people who are working on the right FRs and DPs as represented by the design hierarchy.

System (or product) design and development process may be described in terms of the four domains of axiomatic design shown in Figure 1 (Suh, 1990, 2001). The first domain is the customer domain, in which the attributes and needs of the customers are characterized as Customer Attributes (CAs). The second domain is the functional domain, in which the customer needs described in the first domain are translated into a set of Functional Requirements (FRs). The third domain is the physical domain, which is characterized by a set of Design Parameters (DPs) chosen to satisfy the FRs. The last domain is the process domain, which consists of a set of Process Variables (PVs) that can create the DPs of the third domain. The characteristic vectors, {FRs} of the functional domain, {DPs} of the physical domain, and {PVs} of the process domain are decomposed to the leaf-level FRs, DPs, and PVs to produce a product that satisfies the highest-level FRs.

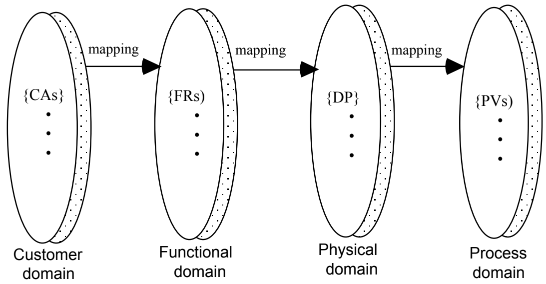

Figure 1 Four domains of the design world

The higher-level FRs and DPs must be decomposed to the leaf-level FRs and DPs. The decomposition is achieved by zigzagging between the functional and the physical domain. Since there may be many DPs that can satisfy a given FR, it is important that the best DP be chosen to produce the most robust design. Throughout the decomposition process, collaboration and negotiation may be needed to accelerate the design process. In axiomatic design the DP we choose for a given FR must minimize the information content.

The concept of four domains has been applied to a variety of different problems, including design of machines, hardware, software, organizations, manufacturing systems, materials, and strategies (Suh, 2001 and 2005). In the following discussions, product design will be used to illustrate the basic concept.

Collaboration in determining the customer needs

Collaboration begins in the customer domain, since we must identify the customer needs accurately since the subsequent design process is directly affected and controlled by them. The process used to define customer needs may depend on the nature of the task. Therefore, the process of collaboration and negotiation in defining the customer needs also differs. Identifying customer needs is a difficult task unless the company has a dominant position in the market and has access to the key customers.

In product development, a great deal of data collection, collaboration, and negotiation are required. The size of the team may be relatively small during the early formative phase of the project, but it grows with the development of the project.

Collaboration and negotiation in determining FRs, DPs, and constraints

Perhaps one of the most important steps in axiomatic design is the establishment of the functional requirements (FRs), which is defined as a minimum set of independent requirements that completely characterize the functions of a product, once the customer’s needs are determined. The ultimate performance of the product is determined by the established FRs. FRs must be satisfied within the bounds imposed on the solution by constraints.

The process of establishing the FRs may involve many participants, although in some cases, one person can establish all the FRs. When many people participate, collaboration and negotiation in determining FRs may play a significant role. Group decisions are preferable when the task is too involved for one person to possess and know all the FRs that a product must satisfy. Unfortunately, when a large number of people participate in determining FRs, the decision-making time increases with the number of participants. To increase the efficacy of the decision making process, we may use axiomatic design principles.

By definition, the FRs are independent from each other and therefore, the design process must choose specific DPs that do not couple the FRs as per the Independence Axiom. An acceptable design that satisfies the Independence Axiom is an uncoupled design or a decoupled design. In an ideal design the number of FRs and the number of DPs should be the same. The design matrix that relates FRs to DPs is a diagonal matrix for an uncoupled design and a triangular design for a decoupled design. When the design matrix is not diagonal or triangular, the design is a coupled design, which is not an acceptable design because of the coupling of FRs. Functional independence, the process of developing uncoupled or decoupled design, and the concept of design matrix are given in Suh (1990 and 2001).

The highest-level FRs and DPs may not be implementable because of the lack of design details. In this case, FRs and DPs must be decomposed. To decompose FR and DP characteristic vectors, we must zigzag between the domains. This is illustrated in Figure 2. From an FR in the functional domain, we go to the physical domain to conceptualize a design and determine its corresponding DP. Then, we come back to the functional domain to create FR1 and FR2 at the next level that collectively satisfies the highest-level FR. FR1 and FR2 are the FRs for the highest level DP. Then we go to the physical domain to find DP1 and DP2 that satisfy FR1 and FR2, respectively. This process of decomposition is pursued until the FR can be satisfied without further decomposition when all of the branches reach the final state. The final state is indicated by thick boxes in Figure 2, which are called the “leaf” or “leaves”.

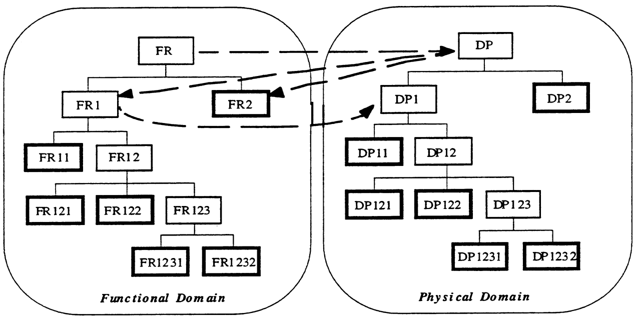

Figure 2 Zigzagging to Decompose FRs and DPs in the Functional and the Physical Domains and to Create the FR and DP Hierarchies. Boxes with thick lines represent “leaves” that do not require further decomposition.

To be sure that we have made the right design decision, we must state the design equation – {FRs} = [A]{DPs} – at each level of decomposition. For example, in the case shown in Figure 2, after FR and DP are decomposed into FR1, FR2, DP1 and DP2, we must write down the design equation to indicate our design *intent* at this level. Since we know that the design must be either uncoupled or decoupled designs, the intended design must have either a diagonal or a triangular matrix. All subsequent lower-level design decisions must be consistent with this high-level design decision. Design Matrix [A] can be used as a governing roadmap for group collaboration and negotiation.

At each level of decomposition, the design decisions made must be consistent with all higher-level design decisions that were already made. That is, if the highest-level design matrix is a diagonal matrix, all lower-level decisions must not make – either intentionally or inadvertently -- the off-diagonal elements of the highest-level design matrix non-zeroes. To check this fidelity and consistency of design decisions, the full design matrix must be constructed by combining all lower-level design matrices into a single master matrix.

To decompose FRs and DPs, the designer must zigzag. We cannot decompose the highest-level FRs unless we first conceptualize DPs that can satisfy these highest-level FRs. Therefore, when we define the FRs in a solution-neutral environment, we have to "zig" to the physical domain, and after proper DPs are chosen, we have "zag" to the functional domain for further decomposition. Details are given in Suh (1990, 2001)

To have an acceptable design, both the FR/DP design matrix and the DP/PV design matrix must be diagonal or triangular. The details of the mapping and decomposition process are discussed in Suh (1990, 2001). In this DP to PV mapping process, the collaboration and negotiation between the designer and the manufacturing engineer is essential to insure that products that can easily be manufactured are designed.

When collaborators in an engineering system development project understand the design process of axiomatic design, they will know what constitutes good decisions in design. They will also be able to seek and convey the right information to other participants based on the design hierarchy. They will know how the information should flow and how collaborators must interact to make the right decision based on the design hierarchy. Without this kind of system, it will be difficult to make decisions by a group of people, who may have different educational and experiential backgrounds.

COLLABORATION AND INFORMATION CONTENT

Collaboration and negotiation will be more effective when all the participants understand how information content is defined in axiomatic design and how the Information Axiom applies.

The Information Axiom states that the information content must be minimized, which means that the final product performance must be within the specified allowable variation for each FR. The information content is zero when the system performance (given by the system range) is always inside the allowable variation range (given by the design range). When the system range is outside of the design range the ratio of the overlap between the design range and the system range determines the information content (see Figure 3). In negotiation sciences, the concepts of BATNA (better alternatives to negotiated agreement) and "reserved value" are critical. Both concepts are related to the information content in Axiomatic Design (Lu, 2006).

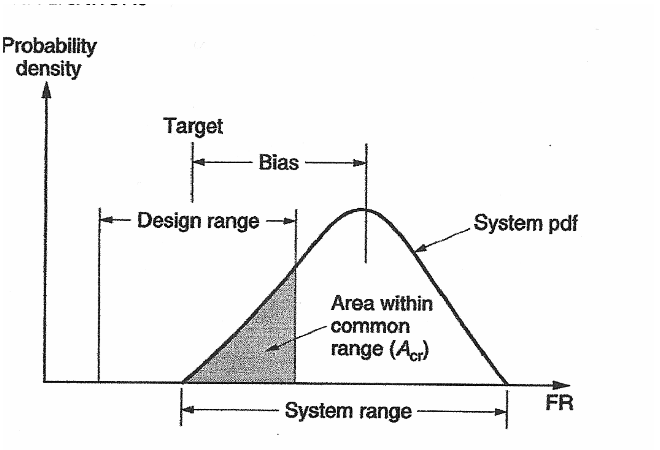

Figure 3 The goal of design decision is to make the system range to be inside the design range. Information content is measured by the ratio of areas of the common range to the system range

The information content *I* of a system with n FRs is defined as

$$\boldsymbol{I}_{sys} = -\log_2 \boldsymbol{P}_{\{n\}} \quad (1)$$

where $\boldsymbol{P}_{\{n\}}$ is the joint probability that all n FRs are satisfied. When the FRs are independently satisfied, Eq. (1) may be written as

$$\boldsymbol{I} = -\sum_{i=1}^{n} \log_2 \boldsymbol{P}_i \quad (2)$$

where $\boldsymbol{P}_i$ is the probability of the system range of FR_i being inside the design range for the FR.

The important implication of the Information Axiom for collaboration and negotiation is that collaborators must seek solutions, i.e., choose DPs for a given set of FRs, that will minimize the information content, and eliminate the waste and inefficiency brought about by "information overload."

COMPLEXITY IN COLLABORATION AND NEGOTIATION

The role of collaboration and negotiation may also be better understood in terms of complexity theory, which extends the notion of information content defined in the axiomatic design theory. When the overlap between the system range and the design range is small, it is difficult to satisfy the FRs and therefore, the task of achieving the FRs appears to be more complex. In other words, the certainty of always achieving the task defined by an FR is governed by the relationship between the design range and the system range of a given FR. Using this observation as the starting point, a complexity theory was advanced, where the complexity is defined as "a measure of uncertainty in satisfying the FRs" (Suh 2005).

Based on this definition of complexity, we can show that there are four different kinds of complexities, all of which have definite implications to collaboration and negotiation in developing engineering systems. The purpose of collaboration and negotiation should be to eliminate or reduce complexity by considering the four complexities.

Four different kinds of complexity

Complexity can be a function of time or can be completely independent of time, depending on whether or not the system range shown in Figure 2 changes as a function of time. Therefore, complexity can be classified into the following two kinds: *time-dependent complexity* and *time-independent complexity*.

Time-independent complexity can be further classified into two different types: time-independent real complexity and time-independent imaginary complexity.

i. Real complexity

As the terms implies, real complexity is a result of not satisfying the FR with 100% certainty. Figure 3 shows the real complexity, which is a consequence of the system range not being inside the design range. Therefore, the real complexity measures the same thing as the information content of the axiomatic design theory.

ii. Imaginary complexity

The imaginary complexity may exist if the decoupled design has more than one FR and if the design is a decoupled design characterized by a triangular design matrix given by Equation (3), which is a decoupled design with n FRs and n DPs:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ \cdots \\ \cdots \\ FR_n \end{Bmatrix} = \begin{bmatrix} X \; 0 \; \ldots \ldots \; 0 \\ X \; X \ldots \ldots \; 0 \\ \ldots \ldots \ldots \ldots \; 0 \\ \ldots \ldots \ldots \ldots \; 0 \\ XX \;\; \ldots \ldots X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ \ldots. \\ \ldots. \\ DP_n \end{Bmatrix} \quad (3)$$

The design represented by Equation (3) satisfies the Independence Axiom if we change the DPs in the order given. If the system range is inside the design range for all FR_i, then the real complexity is equal to zero. However, the decoupled design given by Equation (3) can be a source of imaginary complexity.

This imaginary uncertainty exists only in the mind of the designer when the designer does not explicitly design as represented by Equation (3). If the DPs of the decoupled design are varied randomly without following the order specified by the triangular design matrix, it is difficult to satisfy the FRs of the system and therefore, it appears to be very complex. This kind of complexity is defined as the imaginary complexity. A good example is the combinatorial lock. Although it is simple to open it once we know the numbers and the sequence, it is very complex to open it in the absence of this information. That is, a well-designed decoupled system may appear to be complex if we do not understand the system in terms of the design matrix. Imaginary complexity arises when we lack the knowledge on the system design, because we may not be able to make the system satisfy the FRs. The probability of finding the right sequence of n DPs to satisfy the entire set of n FRs as per Equation (3) is given by

$$\boldsymbol{P} = \frac{1}{\boldsymbol{n}!} \qquad (4)$$

When n is 5, the probability of finding the right sequence is 0.008, which is quite low. Therefore, this design appears to be very complex because the uncertainty is large. However, this uncertainty is artificially created by lack of understanding of the system designed and the situation will become even more complex when a group of engineers is involved.

In addition to the time-independent real complexity and time-independent imaginary complexity, there are two types of time-dependent complexity: time-dependent combinatorial complexity and time-dependent periodic complexity.

iii. Combinatorial complexity

Time-dependent complexity arises when the system range changes as a function of time or occurrence of events. Time-dependent combinatorial complexity can lead to a chaotic situation if the number of combinations continues to explode as a function of time or if the underlying physical phenomenon continues to move the system range away from the design range with the occurrence of events.

An example of a combinatorial complexity is the airlines' flight schedule in bad weather. Suppose that we have a snowstorm around the Detroit area so that airplanes cannot land and take off. Then the airplanes for Boston cannot take off from Detroit. As time goes on, the flights from Boston to other cities will be disrupted since there will not be enough airplanes to dispatch according to the original schedule. Therefore, the airlines will not be able to satisfy their FRs of sending airplanes on schedule. The situation is going to get worse as time passes and the snowstorm continues. This is an example of time-dependent combinatorial complexity. Time-dependent combinatorial complexity arises because in many situations, the effect of future events on the system cannot be predicted *a priori*. Many of these problems are combinatorial problems that can grow more complicated indefinitely as a function of time because the future events depend on the decisions made in the past, but in an unpredictable way. In some cases, this unpredictability is due to a violation of the Independence Axiom.

It is likely that when the collaboration and negotiation leads into a form of combinatorial complexity, they will lead to more chaotic situation and eventually fail. If a system with combinatorial complexity continues to operate for a long time, for instance because the parties involved cannot not collaborate or negotiate (e.g., bankruptcy of a few major U.S. airlines), the system will degenerate into a chaotic state. In this case, an attempt should be made to change this combinatorial complexity problem into a periodic complexity system.

iv. Periodic Complexity

A system with time-dependent periodic complexity may have an uncertainty only within a functional period. This type of time-dependent complexity is defined as time-dependent periodic complexity.

An example is the scheduling of airline flights. Airline flight schedules involve uncertainties in actual flight departures and arrivals because of unexpected events such as bad weather. The delayed departure or arrival at one airport will affect many of the flights and arrival times at other airports. However, once the weather clears, the airlines can resume their regular schedule since the airline schedule is periodic each day. All of the uncertainties introduced during the course of a previous day terminate at the end of a 24-hour cycle if the weather clears up, since aircraft can be relocated during the night when there are not too many flights and resume a regular schedule the following day at 6 am. That is, the combinatorial complexity does not extend to the following day. In a system with a periodic complexity, uncertainties created during the prior period are irrelevant, although during a given period there may be uncertainties.

In case of the airline schedule, the functional periodicity happens to be temporal, but the functional period is determined by the repeating set of FRs. However, there are other kinds of functional periodicity such as geometric functional periodicity and biological functional periodicity.

To reduce complexity of a system, we may transform a system with a time-dependent combinatorial complexity to a system with time-dependent periodic complexity. The idea is to reinitialize the FRs of the system on a periodic basis, i.e., replace combinatorial complexity with periodic complexity. The period is defined as a functional period.

Functional Periodicity in collaboration and negotiation

Functional periodicity is a useful concept both in collaboration and in assuring reliable performance of the designed system.

1. A team collaborating on a project may be more effective if a combinatorial situation in collaboration can be transformed into a periodic complexity by introducing functional

periodicity. A simple example is the introduction of "cooling period" in intense collaboration and negotiation situations. When the collaborators cannot agree on a decision, they should cease to work together for a while and reconvene the discussion anew. In other words, "reinitialize" the collaboration.

2. Similarly the functional periodicity should be built-in In designing systems to insure that system performs a desired set of functions indefinitely by reinitializing the system. This will make the system stable throughout its lifetime (Suh, 2005). The first step in introducing a functional periodicity is to create uncoupled or decoupled systems by identifying a repeating set of FRs. The system must be reinitialized at the beginning of each period.

Implication of functional periodicity on collaboration

The simple case of collaboration is the two-party collaborating on an engineering project. If they find themselves in a disagreement and thus cannot collaborate, they should stop their work and go back and review the highest-level FRs and DPs. If their disagreement is not over the original goals of the project represented by the highest-level FRs, they should follow the FR/DP decomposition tree established by their prior collaboration until they identify the source of disagreement. It may turn out that an intermediate-level FR and DP are the source of current conflict, in which case the design should be modified. In other words, the collaborative design effort should be re-initialized to satisfy the highest-level FRs.

The fact that the collaborators are pleased with their collaboration is *not* a proof that their decisions are correct. There is the possibility that the collaborating team has made a wrong decision and yet is happy with their decisions. To prevent such a situation, a functional periodicity for collaboration should be introduced and force the collaborators to re-initialize their original sets of FRs and DPs. This is in contrast to continuing the same thought process until the end of the project. They may bring in a third party to provide a different view point if it is possible. This process may reveal the mistakes they have made when they discover inconsistencies in their reasoning.

ISSUE OF LOCAL OPTIMUM VS. GLOBAL OPTIMUM

In designing a large system, individual designers and engineers may develop a solution that is perceived to be the best for their part of the project. However, the solution may not be the best solution for the entire system. One of the major purposes of collaboration and negotiation is to be sure that the local solutions are consistent with the overall system solution. The axiomatic design framework provides a framework that enables the checking of the local solutions in a global systems context. This is done by making sure that the decomposition is done consistently from a level of hierarchy to the next level of hierarchy, there is no coupling of FRs by means of the design matrix, and by checking the information content.

CASE STUDY

Saab established their corporate goals, strategies, and plans based on the axiomatic design framework, which was used to guide the work and collaboration among its employees (Nordund, 2006). Nordlund's description of Saab's planning sent to a senior manager of a global U. S. company by email is as follows:

> … I have been involved in several planning and strategizing sessions where we used the method and axioms (primarily the independence axiom) to develop our plans and strategies. In all these sessions it is safe to say that everyone agreed that the result was much better than it would have been had we not followed this approach. The main reasons for the significantly better result were:

- Zig-Zagging: A clear process, everyone knows what we are doing, and what will happen next
- Domains: A clear framework to sort information. Information exists at several different abstraction levels and domains simultaneously. The domains provided us with a framework to sort through ideas, analyze old plans, and information.
- Independence Axiom: Clear decision making criteria that forces a very pragmatic question at every step: in what sequence shall the different parts of the strategy/plan/action be implemented, and are we sure that there are no conflicting parts of the plan.
- Documentation: Very concise documentation that can serve as an index into underlying documents where more details can be captured. This documentation is also useful a long time after the actual planning session(s).

Saab Service Partner's Business plan 1994-1999 is given in Table 1 for illustration of Saab's strategic plan. I am clear to use this document in public, so there is no need for NDAs etc for you to use this internally or externally. The document is in Swedish, and I have made a quick translation for you. I think it is good to see the original where all the executives signed off.

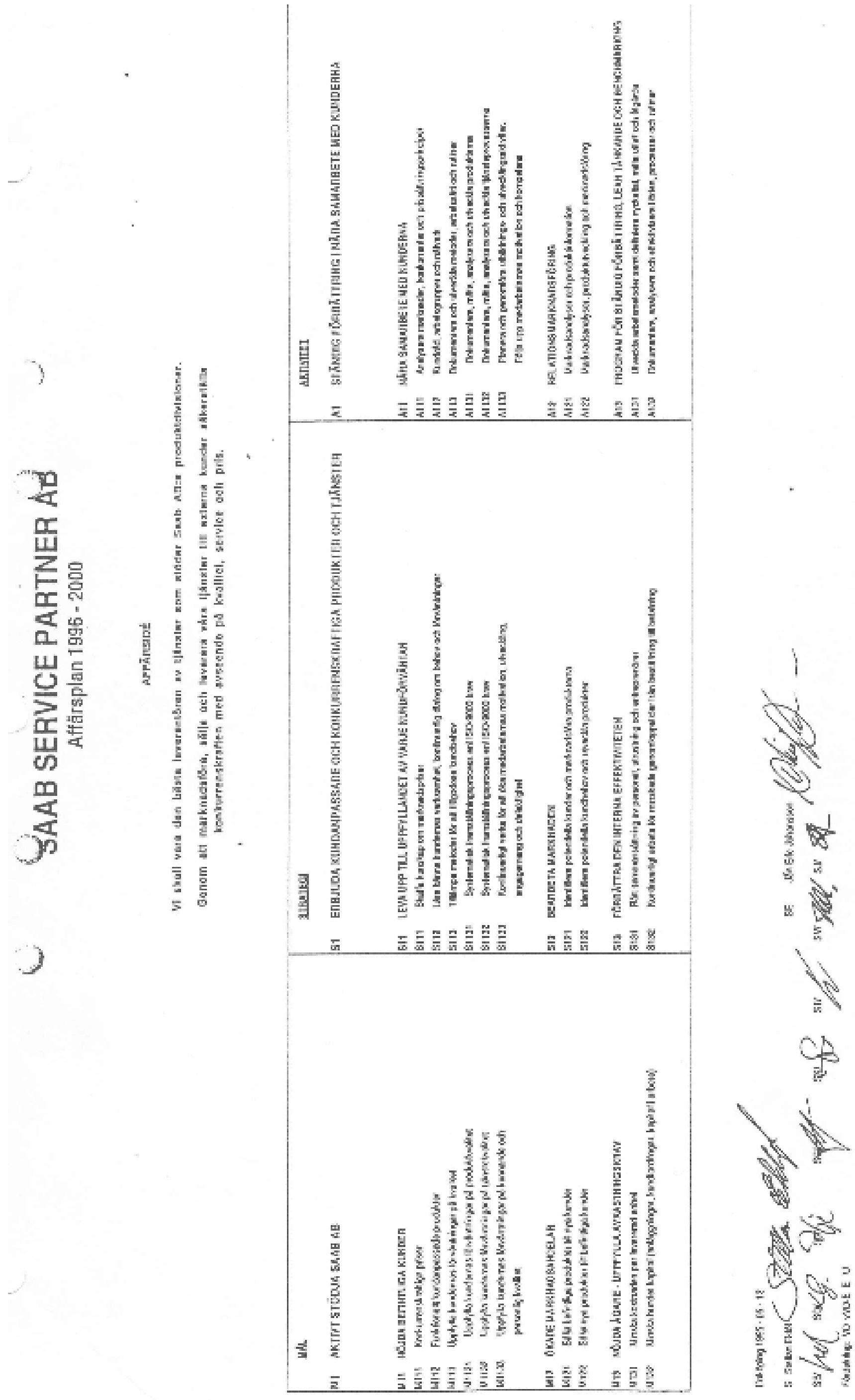

Table 1 Original document of Saab’s goals, strategies and actions

Part of Translation of Table 1:

The top 4 lines cover the business mission.

We used three domains (left customer domain out of it). We renamed them from Functional, Design and Process domains into Goals, Strategies and Activities.

The *goals* translates as follow:

M1 Long term support Saab Aircraft and Defense with our expertise, our products and services
M11 Satisfied Existing Customers
M111 Competitive pricing
M112 Functionally customized products
M113 Satisfy customer expectations on quality
M1131 Satisfy customer expectations on product quality
M1132 Satisfy customer expectations on service quality
M1133 Satisfy customer expectations on expertise and personal quality

M12 Increase Markett share
M121 Sell existing products to new customers
M122 Sell new products to existing customers

M13 Satisfy Owners
M131 Reduce cost per delivery
M132 Reduce restricted equity (equipment, acct payable, WIP)

The *strategies* (I restrict the translation to the top level from here on)

S1 Offer Customized and competitive products and services
S11 Prioritize meeting every customer expectation
S111 Monitor market pricing
S112 Study the customers' business, continuous dialog about needs and expectations
S113 Implement processes to meet customer needs
S1131 Systematic development process according to ISO 9000
S1132 Systematic processes according to ISO 9004-2
S1133 Continuously invest in increasing our employees' morale, competence, loyalty, and empowerment

The *activities*

A1 Continuous Improvement in close cooperation with our customer
A11 Close cooperation with our customers
A111 Analyze markets, competitors, pricing principles
A112 Focus groups (with customers), working groups and networking
A113 Document and develop processes and procedures
A1131 ..

We had a lot of discussions on whether S1133 was a goal or a strategy. It was probably the most interesting part of this whole session, which really made people see the benefit of using axiomatic design. It forced us to really understand the difference of what-how as applied to a company. To keep employees happy is not a goal of a company, however, in successful companies it is an important strategy. In this company's case it was an important strategy to keep their external customers happy.

In addition to this business plan, we also have a public affirmative action plan that I can share (it is also in Swedish). This was the corporate plan for all of Saab-Scania. This document is in the form of a small pamphlet and was distributed widely in the company.

In closing, some general remarks: Since leaving my MIT fulltime position, I have held senior positions in industry. First as director of technology strategy and acquisition at Saab Corporate, and for the last 5 years as vice president of engineering at Saab Rosemount Tank Radar AB. My current company was sold from Saab, and is now part of Emerson Electric Corp since 5 years. I continue using Axiomatic approach when addressing any complex situation with a lot of information and many issues to keep track of. I know of no better way of dealing with complexity.

I comfortably recommend anyone to apply it to planning (I have used it for business planning, technology, market plans, etc.). However, in the first cases it is critical to have a facilitator to run the planning sessions. This is necessary to ensure success. Typically, senior management has little patience for unsuccessful sessions as their time is at a premium (I know from personal experience).

HUMAN ELEMENTS OF COLLABORATION AND NEGOTIATION

Collaboration and negotiation involves real human beings with emotion and self-interest, which introduces another dimension of complication to the collaboration and negotiation process. When humans interact, the social dynamics will change individuals' perspectives toward a problem, hence lead to different decisions. In the case of a single-person project, choosing FRs and DPs will be purely based on their goodness in delivering the ultimate customer's needs. In a collaborating environment involving people, other issues such as job security, workload, liability, individual ego, etc. are likely to play a significant role. These secondary issues may become a dominating factor in collaboration unless they are properly managed (Fisher, et al, 1991; Lee, 2006).

RULES FOR COLLABORATION AND NEGOTIATION

IN DESIGN

The foregoing discussion of axiomatic design and complexity theory yields the following heuristic rules that may help the project and the collaborating participants:[1]

Rule 1 – All participants must agree, before proceeding, on the customer who must be satisfied, and the attributes that the customer is looking for.

Rule 2 – All participants must agree on the highest-level FRs defined for the project through collaboration.

Rule 3 – In establishing the FRs, make sure that the FRs are independent of each other by checking whether they are stating the same thing using different units or words. (FRs are independent of each other by definition.)

Rule 4 – The Independence of FRs is not negotiable.

Rule 5 – In selecting DPs to satisfy the FRs, select the DPs that maintain the independence of FRs by checking the design parameters (acceptable Design Matrix must be diagonal or triangular).

Rule 6 – If possible, check the system range of the FRs chosen against the design range to choose the best DP. (Sometimes, it is difficult to know the system range when the details of the design have not been developed through decomposition.)

Rule 7 – In selecting PVs to enable the creation of DPs, select PVs that maintain the independence of DPs. (PVs are manufacturing processes, but in organizational design, PVs are resources.)

Rule 8 – Check if the chosen PV is likely to satisfy the DP by checking the required tolerance of DPs and the tolerance of a DP that can be created by the chosen PV.

Rule 9 – Complexity should be minimized or reduced.

Rule 10 – Evaluate the collaborative effort to determine if it has the characteristics of combinatorial complexity, which is indicated by continuing deterioration of the output with time.

Rule 11 – Introduce a functional periodicity in collaboration and negotiation by forcing all the participants to review the established FRs at all levels, and reinitialize the project for the following period as a means of preventing the collaboration from becoming a process with combinatorial complexity.

Rule 12 – Check the design matrix periodically to be sure that the collaborative project is not working on an imaginary complexity problem.

Rule 13 – If the system has real complexity, redesign the system starting from the highest-level FRs.

Rule 14 – The impact of changes must be assessed and all affected FRs and DPs must be modified.

Rule 15 – All participants must honor decisions made at higher levels. If the lower-level decisions indicate that the higher-level decisions had a flaw, then the higher-level decisions should be reviewed and corrected.

Rule 16 – Negotiated decisions must be self-consistent throughout the hierarchy.

Rule 17 – Constraints must be tracked and should not be violated.

CONCLUSIONS

The quality and productivity of technological and industrial endeavors depends on the design decisions. Collaboration and negotiation are important elements of group-decision making. To be sure of the decisions are correct decisions, the collaboration process should use axiomatic design framework as a means of eliminating as much subjectivity as possible. The current ad hoc process of collaboration and negotiation should be supplemented with scientific principles and approaches established by axiomatic design. Key points made in the paper may be summarized as follows:

1. Collaboration and negotiation in developing engineering systems are necessary.
2. The field of collaboration and negotiation in engineering needs to establish basic principles that can make the field more rational and efficient by removing subjective elements in decision making.
3. A set of rules is proposed that can be used by all participants in engineering system design to promote further discussion.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the helpful suggestions and comments made by Professor Christopher A. Brown, Dr. Taesik Lee, Professor Stephen Lu, and Dr. Nannaji Saka, and the

[1] These rules have not yet been tested and verified for correctness.

editorial assistance of Mr. Tony Pulsone. This research was funded by the Park Center for Complex Systems at MIT.

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