System Architecture Evaluation by Single Metric

By

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Abstract

System architecture is driven by numerous upstream influences. Regulations, market forces, cultural biases, and a variety of other influences can significantly affect whether architecture is successful or not. To be successful the architect must include upstream influences in the design. Few if any architectural methods are available to systematically account for upstream influences. A new method, Evaluation by a Single Metric (ESM), is presented. It is based on fundamental design principles. It enhances the system architectural process by organizing upstream influences that drive architecture. The ESM method is concept independent and used before concept focused system architectural methods. Specifically, system boundaries, salient upstream elements, and functional connections thereof are systematically determined. The ESM process provides a concept neutral framework used to evaluate candidate architectural concepts. The ESM method is very general. It can be used for the design of nearly any kind of system or process. The thesis makes extensive use of a diverse set of examples which highlight ESM advantages and flexibility.

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System Architecture Evaluation by Single Metric

Preface

The genesis of this work stems from the System Architecture (SA) course, which is part of the MIT System Design and Management core curriculum. System architecture research is relatively new despite the fact that as a discipline it has been practiced for centuries. Even though the SA course was rich in content and scope there was little cohesion between principles, methods, and heuristics presented in class. Eberhardt Rechtin's text (Reference 1) provides excellent system architecture information. It was used extensively throughout the generation of this work. However, it also fails to provide upstream system architecture methods. The goal of this thesis is to provide a comprehensive method that system architects can use to develop more complete, robust, and elegant system architecture. In particular the evaluation by a single metric (ESM) method gives the system architect the means to identify and organize upstream influences. This method is not intended to replace favorite methods an architect may use for conceptualization. It is to be used before the conceptualization process.

The intent of this work is to foster better engineering system architecture. However, the method described is found to be applicable to non-traditional engineered systems. A diverse set of examples is used to illustrate the evaluation by a single metric (ESM) method.

Many artistic, engineering, and traditional architectural terms and phrases are used throughout the text. In order to grasp some of the abstract concepts and descriptions you need to have some architectural experience. If you are more familiar with system engineering problems the ESM method can be used in such contexts. However, the architectural design benefits are mitigated in system engineering work because the concept is often known.

Introduction

When asked "what makes good architecture" one gets many definitions. When you take these responses and boil them down you end up with something like "everything works well together". These four words tell the architect what to do. Together means everything has to be connected. Works means everything is working towards the same purpose. Well is a measure of the efficiency or elegance of everything working together. Notice the word "everything" has been the subject noun for the last three sentences. Determination of what constitutes "everything" is crucial to the architecture at hand. Eberhardt Rechtin echoes the same statement on page 43 in Ref 1. It is up to the architect to define what everything is, and then how it all works together. If one includes too many or too few "things" only a poor or inadequate solution will be attained. By judicious and iterative selection of things the architect attains a solution and increases the elegance of design.

The ESM method is intended to answer the following fundamental questions. How do you; define "everything" in the system, functionally connect everything, and organize everything such that disjoint architectural concepts can be objectively evaluated?

The ESM method starts at the very beginning of the process. Many relevant system elements can be identified upstream of concept selection. Without a thorough understanding of the upstream elements inadequate architecture often results.

The thought of evaluating architecture by a single metric may sound over simplified, based too much on numbers, and not enough on judgement. The fact that an architect must define *the* most important result of his work is one of ESM's strengths.

Upstream Influences on System Architecture

Well before the fist line is drawn for a "clean sheet of paper" design the architect has a host of issues to contemplate. Everything that must be identified and organized before architecture begins is defined as upstream influences. Figure 1 taken from Reference 2 diagrams some of these elements. Based on experience or intuition a designer captures most of the upstream elements. The more familiar the system, the less likely a salient element is missed. System engineers who deal with less ambiguity than architects can rely on rules developed from past experience. Architects on the other hand tread into new design spaces where old rules do not necessarily apply.

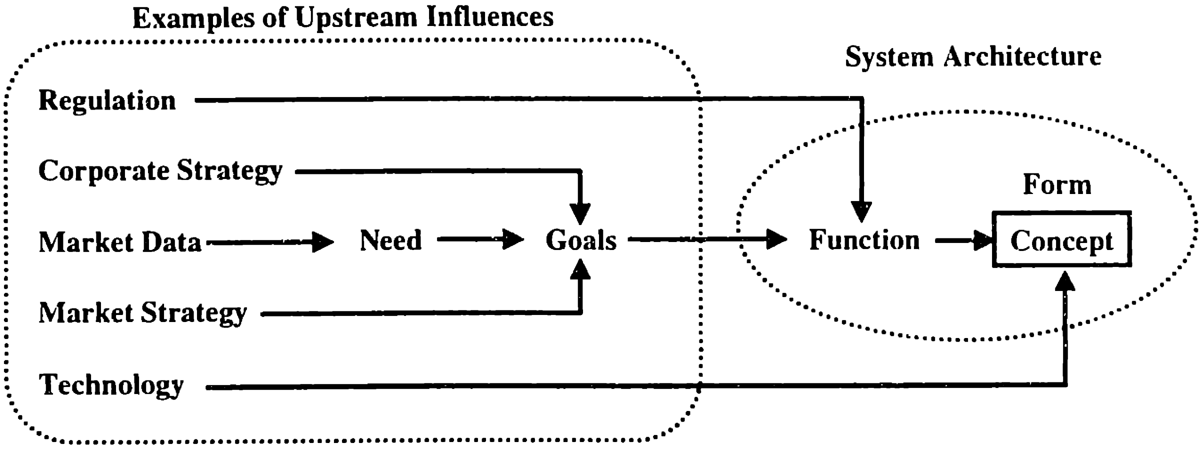

Figure 1. Concept independent upstream influence flow into system architecture

There are many examples of inadequate consideration of upstream influences. Some of the best examples come from the aerospace industry. The F-20 Tigershark was a dismal failure for Northrop. The uninformed onlooker might say the plane was obviously no good. Actually the F-20 was an astounding aircraft. The chief *aircraft* architect did a fine job. The *business* architect faltered. It was designed to be a follow on to the very successful Northrop F-5 fighter. It was the best light weight fighter in the world. Because it was a derivative, its price was very good with respect to its capabilities, which made it dollar for dollar the best fighter value in the world. These characteristics were thought to be good enough to have the aircraft sell itself.

Unfortunately some upstream elements were not considered. Third world countries had a political problem with a derivative aircraft. Despite the F-20's economy it still presented a substantial expense for smaller countries. There was not enough prestige with a derivative to justify the expense. Countries therefore chose "newer" and more expensive aircraft to satisfy political constituents. The biggest business planning deficiency was the lack of U.S. Air Force acceptance. Many friendly countries are tied into the USAF logistics system. Countries said they would purchase the F-20 if it were in USAF inventory. The USAF was already committed to the F-16 and could not afford the F-20 monetarily or politically. Whether these factors were omitted from planning or their profound influence on marketability was underestimated is unknown. It is obvious that they should have been addressed either by aircraft design or some other means. After investing $1.2B between 1980 and 1986 Northrop canceled the program having not sold one aircraft (Reference 3).

Rechtin discusses other hard-learned lessons in Ref 1. An ICBM system built without a confirmed basing mode. An ABM missile system begun without a solution to offensive saturation. Software packages overly sensitive to human error. Manufacturing plants built without future flexibility. The errors made in these cases stem from not identifying a system relevant element or not functionally connecting the element within the system. The ESM method was specifically addresses this problem.

Overview of the ESM Method

The ESM method offers a number of advantages for the architect. ESM can also be used for a variety of problems. Six examples have been selected to illustrate advantages and flexibility.

There have been countless problem solving methods proposed by experts, and so called experts over the years. Many methods are variants of each other. These "derivative" methods have been called JAM's (Just Another Method) by some people[1]. Evaluation by a Single Metric is another method. However, there is a big difference between ESM and other methods. ESM is based on a cohesive set of principles. Like a mathematical proof which builds from a universally accepted starting point ESM builds on fundamental principles to an end method.

ESM is based on the five following principles. A reference has been provided for each to substantiate its validity. In general your comfort with ESM should reflect your faith in these principles.

Principle 1. "Everything is part of a higher level super system and everything is composed of sub systems". This principle is true of mechanical, electrical, biological, celestial, and every other kind of system. Humans' ability to comprehend the complexity of their environment and to alter it in complex ways is unique. Though the explanation of man's capability is subject to great discussion, clearly the ability to decompose problems, be they one of understanding or creation is a major factor. No single person can comprehend all the elements of nearly everything man creates. Yet the complexity of man's knowledge and creations increase every day. ESM decomposes problems based on this principle.

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[1] First heard by the author from Matts Norlund, SA teaching assistant, 1997. Acrynym origin is unknown.

Principle 2. "The architect must think holistically of-the-whole in order to identify high points of leverage"[2]. In any given system there are strong and key elements that govern results. The architect must identify all salient elements and understand the leverage of each. ESM offers a comprehensive and quantifiable approach to identify levers and their relative powers.

Principle 3. "Only one function can be optimized for a system, all other objectives are constraints"[3]. Inevitably there are conflicting objectives with any architecture. System performance and cost are classic conflicting objectives. ESM forces the architect to decide early in the process what objective is to be optimized.

Principle 4. "An optimized system is not necessarily the sum of local optimizations"[4]. ESM offers a quantifiable view of the system as a whole. This enables the system to be optimized and not the parts.

Principle 5. "Design methods do not solve problems, they only help you organize the problem, ask the right questions, and guide you to the best solution"[5]. This is also true of ESM. An ESM strength is the comprehensive system map it provides. The architect can see organization, ask questions of each element, and evaluate solutions.

The ESM method is comprised of eight steps as shown in the process flow chart in Figure 2. Each subsequent step in the process furthers the definition of upstream architecture as well as checks the appropriateness of each previous step. The ESM method is an iterative process. If unsatisfactory results are had the architect must back track to find the root of the problem. In some cases you may have to go back to step one. In other cases an iterative loop may set up over the span of a few steps. When the architect satisfactorily

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[2] As stated by Ed Crawley, SA professor, 1997

[3] Tom Magnanti, System Optimization professor

[4] E. Golldratt, "The Goal", second edition, 1992

[5] Paraphrase of a statement made by Nam Suh, director of mechanical engineering at MIT and creator of the Axiomatic Design method.

reaches the last step he has a unified and consistent organization of all architecture governing influences.

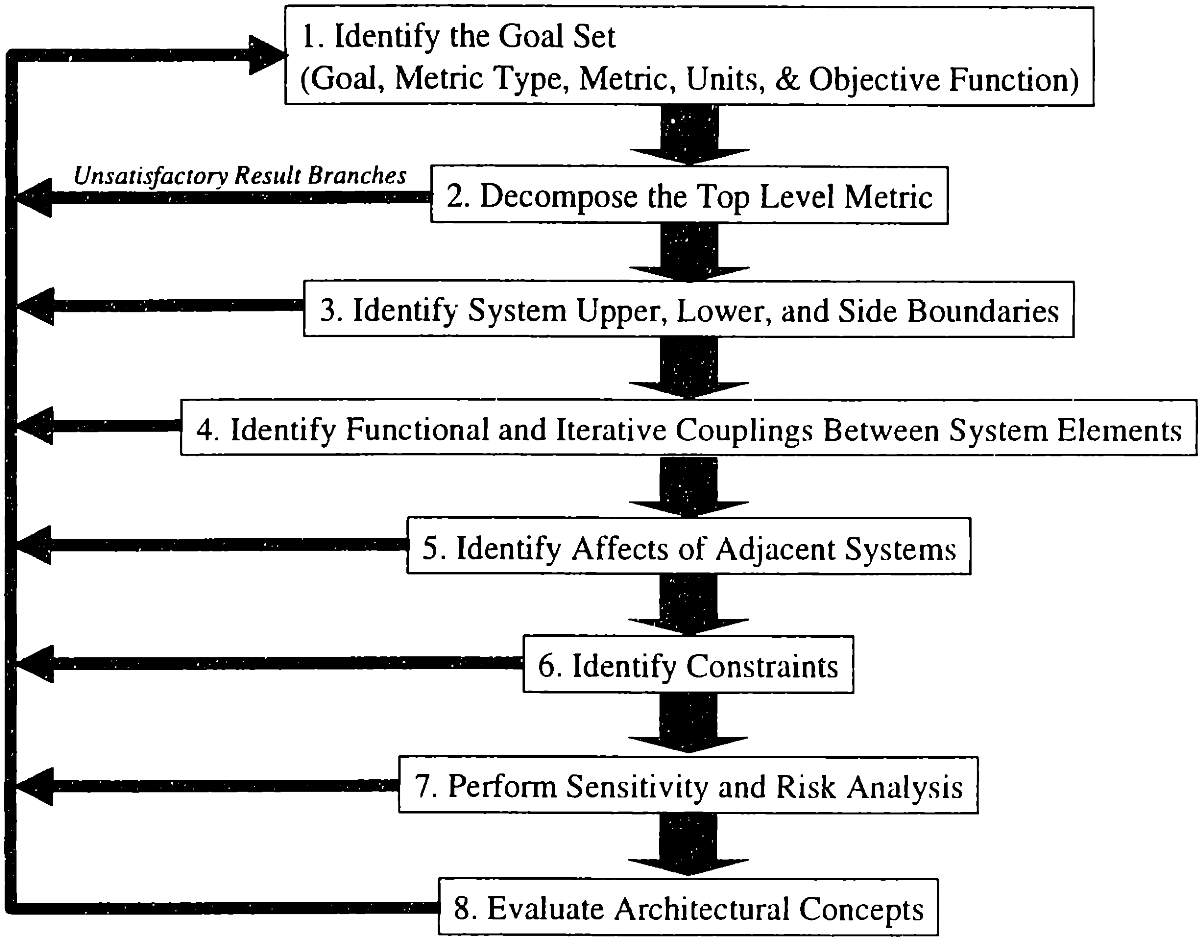

Figure 2. Evaluation by Single Metric process flow

It is important to see the ESM method as a whole before diving into the application details. If too much information were given on each step you would not know where we were going and quickly loses the cohesive nature of the method. A brief description of each step is provided. The steps are generically explained without examples you do not confuse particular example aspects with fundamental rationale for the step. This approach is done at the expense of some ambiguity. Some of the step descriptions may seem abstract. You are encouraged to look ahead at some of the figures as you read through the generic descriptions. Examples best demonstrate how to execute the ESM method and illustrate advantages of its use. As you read through the examples in the following section the reader is encouraged to refer back to the generic step descriptions below and relate such to the example at hand. After the example section the reason for this format it should be evident.

Step 1. Identification of the Goal Set, (Goal, Metric type, Metric, Units, & Objective Function)

If principle 1 is true then at some high level the architecture of any subsystem can be characterized by a very small set of characteristics. The proper identification of this architectural focal point is crucial. The more you can define your goal the better off you are. Goal, metric type, metric, units, and objective have subtle but distinct meanings. Each is specifically defined in the ESM method. As a group they are referred to as the 'Goal Set'.

Goal

The goal is a very short statement of what you are trying to do. "Land a man on the moon and return him safely to earth" is a classic goal statement. E. Goldratt's book named "The Goal" states that a company's goal is to make money, period. Statements like these have power in their simplicity. The key to forging a good goal is to keep it simple. Many times people confuse goals with constraints. President Kennedy's full statement was "Before this decade is out we will land a man on the moon and return him safely to the earth." "Before the decade is out" is a constraint. Time is not something in and of its self to be accomplished.

Metric Type

Once a goal is identified it can almost always be categorized in one of four ways, numerically, esthetically, spiritually, or objectively. Examples of each type are given in Figure 3.

Metrics Fall Into One of Four Types

Metric Type	Generic and Specific Examples
Numerical	Physical quantities ------- Size, Weight, Power, Volts, ... Monetary amounts ------- Savings, Income, NPV, Debt, ... Non-dimensional -------- Probability, Efficiency, ...
Esthetic	Performing arts ----------- Plays, Movies, Humor, ... Visual arts ----------------- Paintings, Sculpture, Industrial Design ... Literature ------------------ Books, Poems, Articles, ... Architecture --------------- Buildings, Landscape, ..
Spiritual	Internal change ------------ Education, Religion, Stress, ...
Objective	A state change ------------- Land on mars, Climb Mt Everest, ...

Figure 3. Examples of the four metric types

Many things are evaluated numerically; performance, revenue, probability, and many other familiar metrics are a single or aggregate of numerical metrics.

The performing, visual, and graphic arts as well as some consumer products are good examples of esthetically evaluated architectures. Esthetic metrics are emotionally based. They are not directly quantifiable. Esthetic metric evaluation varies from person to person. Qualitative evaluations are based on your own and observed emotional responses or others. Laughter, fear, excitement, and a host of other emotions are evoked by “artistic” architectures.

Spiritual metrics have the same characteristics of esthetic metrics except the results and evaluation thereof are internal to the architect. There is little of no basis for outsiders to evaluate results.

The attainment of an objective, like a numerical result is clearly evident to all. However, objectives do not lend themselves well to quantification. The objective of "landing a man on the moon and safely returning him to earth" is a classic objective metric. Either you do it or you do not. There is little in between.

Sometimes metric types can become mixed. Often the three non-numerical metrics are indirectly evaluated numerically. Sometimes, although not as often, non-numerical metrics can be mixed as well. For these reasons the four metric types can be viewed as a continuum connected in three dimensional space as shown in Figure 4. It may be possible to have a three metric mix but I have not come across one yet. Mixed metric examples are given in Figure 5. The first metric is the real goal, the second is the means by which it is evaluated. For example an esthetic-numerical mixed metric is common in the movie industry. The esthetic qualities of the film are judged by numerical ratings on a survey.

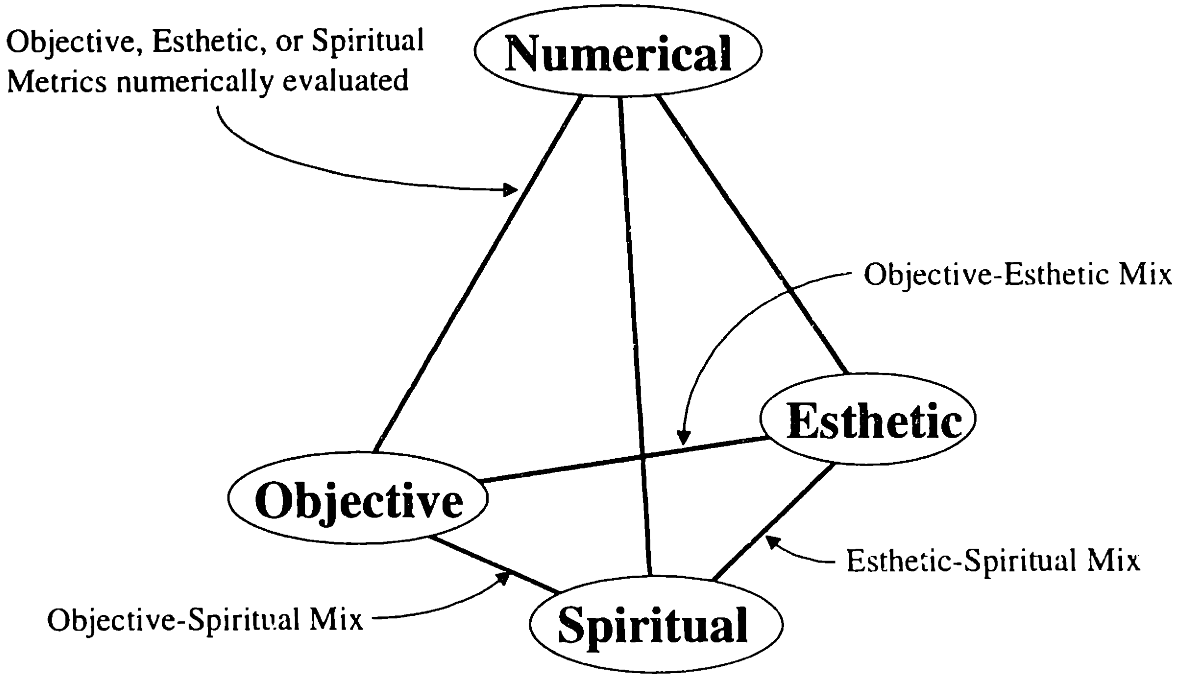

Figure 4. Three dimensional map of metric types

Mixed Metric Type	**Examples**
Esthetic-Numerical	Movie Ratings evaluated by survey results
Spiritual-Numerical	Educational progress evaluated by grades
Objective-Numerical	Attain genius state by I.Q. score
Esthetic-Objective	Artistic ability evaluated by winning first place in a contest
Spiritual-Esthetic	Become a "better person" by assessing comments made by others
Spiritual-Objective	Increased knowledge attained by receiving a college degree.

Figure 5. Examples of mixed metrics

Metric

The metric, or measuring stick, for the architecture is crucial. It is well known that choosing an inappropriate metric can lead you down the wrong path. It is also rather difficult to choose the best metric early in the process. ESM constantly challenges metric selection in steps two through eight. It is particularly important to choose numerical metrics with care. Because we all have our own biases it is easy to select one that favors certain aspects of architecture or even ignores other salient parts.

Units

As will be seen in the metric decomposition, consistency of units is a powerful check on the selection and functional connections of "things" within the system boundaries. Forcing the architect o attach units to elements clarifies the meaning of each. It helps to eliminate double bookkeeping, conflicts, and omissions. Esthetic, objective, and spiritual metrics by definition do not have units unless the architect chooses to quantify as mentioned earlier.

However, a description of each system element can be attached to nonnumerical elements. These definitions show the same benefits as units on numerical elements.

Objective

Driving the objective function to a maximum, minimum, or a given value optimizes a system. If the goal, metric type, metric, and units are consistently stated the objective should be clear. Goals that are objectives tend to have a desired end state. Therefore the optimization is on minimizing a cost such as time and or money. Constraints are an integral part of architecture. It is better to populate the design space with possibilities before one starts paring down ideas based on constraints. This heuristic is used in ESM by virtue of the fact that constraint identification is postponed until step six.

The goal and metric have to be succinct and consistent in order to satisfy principle 3. If one finds it difficult to identify what to optimize usually there are too many goals. All but one have to be viewed as constraints or some composite weighted metric will have to be created.

Step 2. Metric Decomposition.

This step enables the architect to identify all salient elements within the boundary and their functional connections. Or more simply stated everything the architect has to worry about and how they relate. Elements are defined as each "thing" in the system. Metric decomposition starts with the goal metric. Then the metric is decomposed in a tree like structure.

Metric Decomposition is solution neutral. This is a fundamental characteristic and requirement of this step. No concept is necessary. Once a concept has to be defined the threshold between upstream influences and concept architecture is identified. Five to seven levels of decomposition are often possible before reaching an element that requires a concept.

Principles and heuristics often make excellent criteria for decomposition. Principles by definition very rarely lead one astray. Therefore building decomposition off a principle is a sound approach.

Step 3. Boundary Identification

Metric decomposition stops when one of three things happens to a lowest level element; changes in that element's state make insignificant changes in the objective, the architect does not have control over the element, or the element can no longer be decomposed without selecting a concept. This criterion sets the lower boundary.

The edges of the architectural boundary are a fall out of the decomposition. Inspection of the result often includes unexpected elements. Sometimes elements the architect was expecting are not included. The architect needs to evaluate the correctness of the result by challenging each decomposition level. If the metric decomposition is sound then in both cases the unexpected or missing elements are correct. If so metric decomposition has provided the benefit of identifying the proper set of elements that may not have been obtained by intuition alone. If it is obvious that irrelevant elements are present or relevant elements are missing the goal is most likely incorrect and must be modified.

Step 4. Functional and Iterative Coupling of Elements

The lowest level elements are those over which the architect has control. Almost all architectures have interaction between these elements. Some elements are a function of another. Some elements are coupled by being functions of each other. It is important for the architect to identify these interactions. They can cause favorable or unfavorable synergistic effects. Good architecture exploits the former and minimizes the latter.

A design structure matrix (DSM) is used to identify interactions and couplings among the lowest level elements. Rearranging the DSM result to a lower triangular matrix identifies which elements have to be considered early in the conceptualization process. The DSM also identifies which elements make up iterative decision blocks. The resulting decision flow diagram is a powerful tool for organizing the conceptualization process.

Step 5. Adjacent System Interaction

Often the top level metric goal is influenced not only by the system of interest but also by adjacent systems. For example a building's appeal is a function of its architecture and the surroundings. Neighboring buildings, landscaping, and other elements constitute an adjacent system that influences an architects decisions. In some cases the architect has no control of adjacent system elements, in other cases he or she does. This step identifies adjacent systems, their respective lowest elements, and how they affect the decision flow found in step 4. Adjacent system identification is performed intuitively. Lowest level elements are found by metric decomposition. The adjacent system element's affect on decision flow are found by DSM application.

Step 6. Constraint Identification

As with any design problem there are constraints. A constraint is defined as limits over which the architect has no control. Budgets, time, size, and a like are familiar constraints. Constraint consideration must be given to each metric decomposition element. Design freedom will be constrained if there are significant constraints on the early decision elements found in steps four and five.

Step 7. Sensitivity Analysis.

Steps two through six allow the architect to see the entire system and which elements most significantly influence the top level metric. Two facts, metric sensitivity to element changes and the latitude available for an element to change govern influence. The first fact is much like a partial derivative. For every unit change in an element you get a corresponding change in the top level metric. The second fact is borne out in step 6. Even though a top level metric may be very sensitive to an element the amount of change available to that element may be very limited.

Numerical metrics lend themselves well to sensitivity analyses. Sensitivity analyses of non-numerical metrics can be done by inspection and prove equally valuable to the architectural process.

Step 8. Architecture Evaluation.

At this point system architecture conceptualization can begin. Decisions are made regarding the first elements identified in steps four and five in light of the sensitivity results. Each disjoint architecture is evaluated by how well it satisfies the objective function identified in step one. Like the sensitivity analysis, numerical metrics lend themselves well to numerical evaluation. Non-numerical metrics are evaluated subjectively.

Architecture concepts can be derived from any familiar method; analogy, form and function, axiomatic design, TRIZ, etc. It is important to restate that these methods are concept dependent where as all the ESM steps are concept independent.

ESM Application Examples

The purpose of the preceding section was to outline ESM mechanics and rationale for each step. Examples listed in Figure 6 are used to illustrate ESM benefits. Examples also provide substance and context to some of the abstract descriptions presented. You are encouraged to refer back to the overview description as examples unfold step by step.

Example	Metric Type	Illustrated Benefits
All examples		Setting boundaries Identifying salient elements Organization of elements
Creation of a Work of Art	Esthetics	Method Overview Need for each step Principle & heuristic use
Needle Floating on Water	Objective	Alternate decompositions Opening up the design space
Meeting Table Design	Objective-Numerical	Working with chunks Concept generation by graphical integration
New Product Design	Numerical	Numerical evaluation Control of upstream influences Importance of outside systems
Team Project	Numerical	When another architect is needed
Thesis Design	Spiritual	My use of ESM How did ESM help or hinder thesis' persuasiveness?

Figure 6. Examples used to illustrate ESM benefits

Example 1 Work of Art

This is an esthetic example, one that is relatively simple, very visual, and easy to grasp. A non-numerical example was chosen first because it is less complex. The fact that it is a bit astray from traditional system architecture domains has another benefit. Unless you are steeped in art theory the system elements may look unfamiliar. By working through the

ESM method the reader should gain an appreciation for the architecture that goes into the creation of a work of art[6]. The ESM method can be used not only for the creation of system architecture but for understanding the architecture of existing systems.

Let us say we have an opportunity to submit a piece of work to a gallery for an up coming show. Our past experience is in the visual arts which includes painting, drawing, and sculpture. What should we do? This is an architectural question.

Step 1 requires a goal set to be established as shown in Figure 7. The first rule in art is that there are no rules. Every artist has his or her own style. This example reflects my style that has proven successful in the past. Other artists may have completely different approaches but in general all are striving for the goal set shown.

Goal Set
Artwork Creation

Goal	Capture feeling of "__________"
Metric Type	Esthetic
Metric	Emotional Response
Units	N/A, (qualitative assessment)
Objective	Maximize emotional response

Figure 7. Goal set for artwork creation

The common goal of art is to capture some feeling. It can be anything, happiness, fear, nostalgia, etc. The particular feeling is not necessary to identify at this point. The metric is the amount of emotional response by the viewer. Purely speaking there are no units. But

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[6] The author has significant rendering experience and several aviation related works of art in museums including the National Air and Space Museum.

there are ways to indirectly numerically measure response. For example if humor were the goal one could measure the length and loudness of laughter and call them humor units. The artist's job is to maximize emotional response.

Figure 8 illustrates a metric decomposition for a piece of visual art. It starts with the goal, "capture a feeling". The key question to be asked is "what is the goal comprised of? Principles and heuristics offer valuable answers to this question. They work well as decomposition criteria because they are by nature comprehensive and irrefutable. The subject the artist has selected and how well the artist executed the work is a common artwork evaluation heuristic. These two elements constitute level 2 in Figure 8.

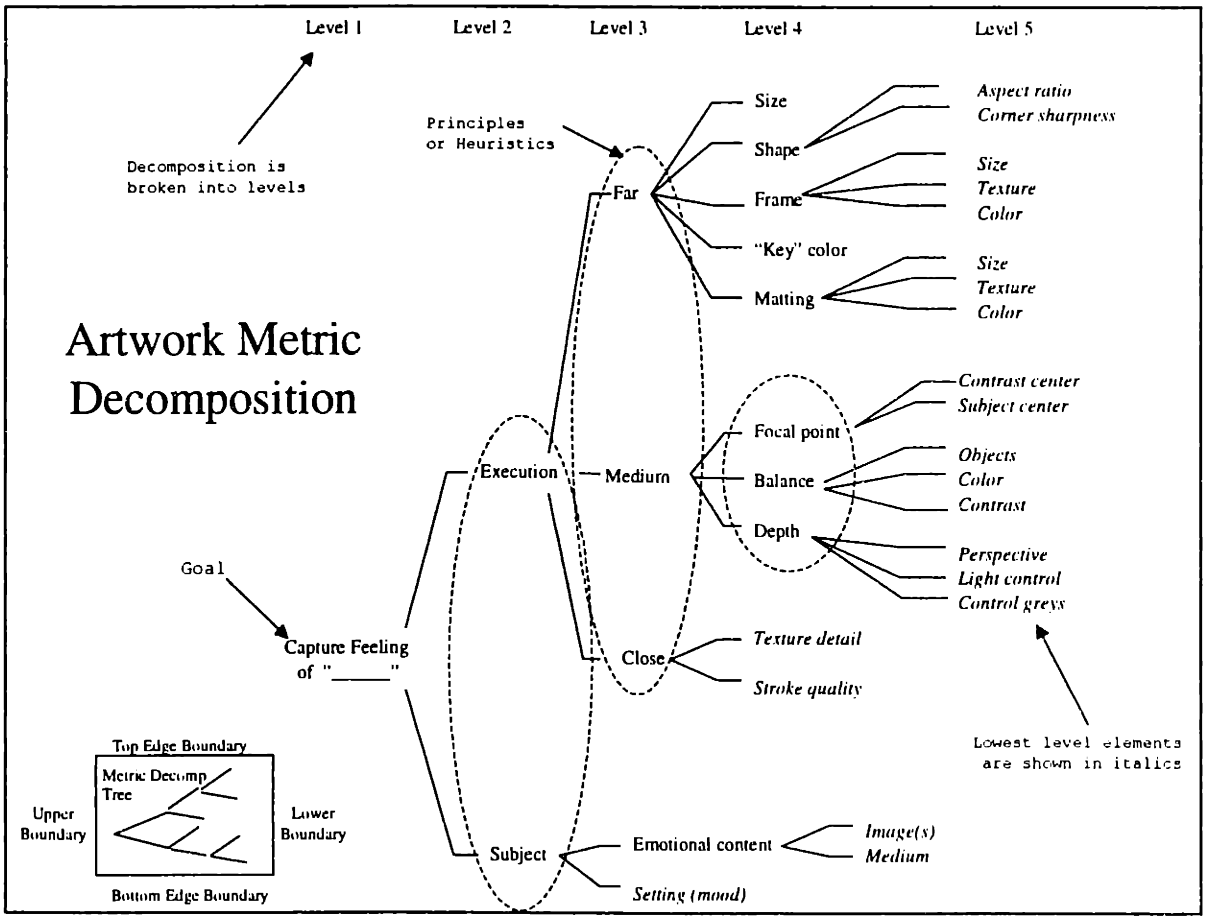

Figure 8. Artwork metric decomposition and boundary definitions

The artist must choose a subject that will maximize the feeling. The subject branch has only a few elements but they are very important. For example if the feeling to be captured was nostalgia the subject might be an old car, old clothing, or some combination of objects. Some objects have high emotional content such as steam engines, classic glass Coke-a-Cola bottles, or slide rules. The emotional content is a function of the medium as well as the image(s) selected. Identical images drawn in pastel and watercolor will foster different emotional responses. The subject must be placed in a proper setting so as to create a proper mood. A glider sitting on the ground does not convey the freedom of flying near as well as the same glider in flight.

How well the artist renders the object is as important. If the subject was a sunset and the artist can only do pen and ink drawings there is a good chance execution will be lacking. These two elements decompose the top level goal because together they drive the amount of feeling captured.

A principle used to decompose execution states a piece of work should look good at far, medium, and close distances. Architects use this principle for building exteriors. The site layout determines building character at far distance. Building geometry determines medium distance aesthetics, and surface details determine up close character. Far, medium, and close qualities are a function of the elements shown in level 4. An artwork's quality as viewed from afar are governed by the physical qualities of the work, size, shape, frame, and matte, and the overall 'key' color. Key color is the dominant color of the work. Landscape paintings tend to be in green hues. Portraits are often in hues of dark brown. Sometimes there is no key color. Either way the key color is often the first characteristic that interests the viewer. The physical aspects surround and hopefully resonate with the key color to make good far view qualities.

Medium distance views relate to the central part of the work. Medium distance can be considered the normal viewing distance. Focal point, balance, and depth drive the medium distance qualities. Focal point is where the eye tends to go first. For a portrait it is almost always the eyes of the person. For a sunset it is usually the apex of the rays of the sun. Balance refers to how well objects, color, and contrast are spread around the work. Too much of any on one side or the other makes the work look lopsided. Depth refers to the three dimensionality of the work. In some cases this is not important. In others it is crucial. Proper perspective, the use of light and shadow, and the amount of gray used in the paint govern depth. A close view is when the work is so large it is beyond your peripheral vision. This happens when you get within a few inches of a piece for artwork larger than about four feet square. At this distance the work's texture and stroke quality drive your impressions.

Step 3 forces the architect to challenge system boundaries. The lower boundary is set by the lowest level elements in Figure 8. These are the things the architect can directly control. The next step is to look at the upper boundary. A professional artist may be more concerned with making money than making the best piece of work possible. Figure 9 shows profit being up two levels. It is comprised of revenue, which is assumed to be a direct function of performance, and cost, which would be some function of materials and time. The profit goal would make the artist trade performance for cost in order to maximize profit. For this example let us assume that costs will be nominal and can be ignored for the first pass through the ESM method. The edge boundaries fall out of the metric decomposition. Therefore the boundaries are set as shown in Figure 8.

You may have noticed that some of the lowest level elements are a function of others. For example the setting and key color are definitely related. Dark cool colors have a much different appeal than bright warm colors. All functional and iterative couplings are identified in step 4. The results for this example are shown in Figure 10. The vertical and horizontal axes are comprised of the same list of lowest level elements. The vertical axis elements are to be decided. The question is what information is needed from the horizontal axis in order to make decisions. For example to determine frame size the size of work and the size of the matte (if it has one) has to be known. Similarly we see that matte

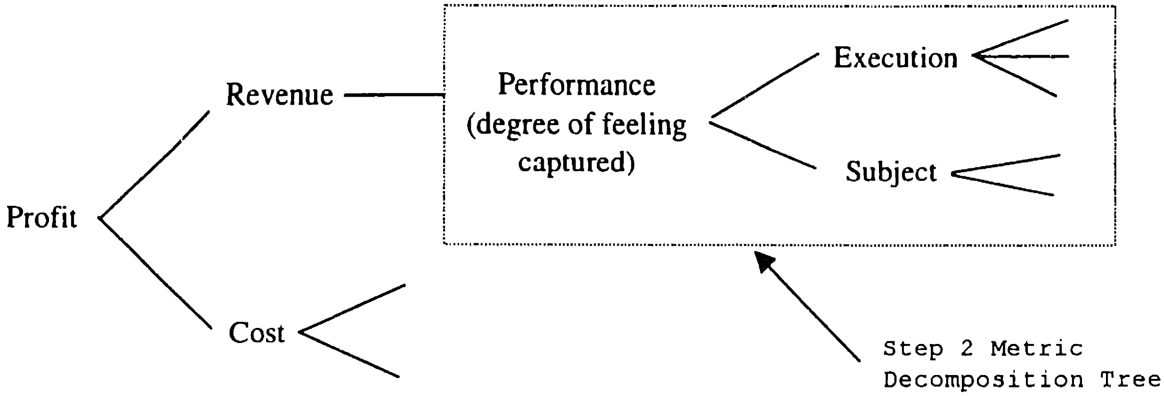

Figure 9. Upper boundary expansion from initial artwork goal

size is driven by the size of the work and frame size. So frame and mat size are a function of the size of the work. This is a functional relationship. Yet frame and matte size are a function of each other. This is an iterative relationship. The beauty of DSM it its ability to identify and group these relationships. A system of weak (W), moderate (M), and strong (S) indicators were used for increased analysis fidelity. Figure 11 is the same as Figure 10 except the rows and columns have been rearranged to give a lower triangiularized matrix. Rearrangement clearly shows which elements drive the design and which are within iterative relationships. The results show images and setting to be the two most important design parameters. Everything either directly or indirectly flows from these two elements. Notice that the frame and matte selection come at the end of the decision flow and are caught in an iterative relationship.

B

Elements that A elements need for decision

A

Elements to be Decided

	Size	Key color	Aspect ratio	Corner shape	Frame size	Texture	Color	Matt size	Texture	Color	Contrast center	Subject center	Object balance	Color balance	Contrast balance	Perspective	Use of light	Use of grays	Texture details	Stroke quality	Image(s)	Medium	Setting (mood)
Size	-																						
Key color		-																					S
Aspect ratio			-																		M		
Corner shape				-																	M		
Frame size	S				-			S															
Texture						-			S														S
Color		S					-			S													S
Matt size	S				S			-															
Texture						S			-														S
Color		S					S			-													S
Contrast center			M								-	S			M		M						
Subject center			M								S	-			M								
Object balance													-								S		
Color balance		M									W	W		-							M		S
Contrast balance		M													-		S				M		S
Perspective			M													-					S		
Use of light											M						-		W			W	S
Use of grays																W		-			M		M
Texture details																			-		S	M	M
Stroke quality																				-		S	S
Image(s)																					-		
Medium	W	M																	M		M	-	S
Setting (mood)	M	M																			M		-

Figure 10. DSM for lowest level elements of artwork metric decomposition

B

Elements that A elements need for decision

A

Elements to be Decided

	Image(s)	Setting (mood)	Size	Key color	Aspect ratio	Corner shape	Object balance	Perspective	Use of grays	Medium	Texture details	Stroke quality	Use of light	Contrast balance	Color balance	Contrast center	Subject center	Frame size	Texture	Color	Matt size	Texture	Color
Image(s)	-																						
Setting (mood)	M	-																					
Size		M	-																				
Key color		S		-																			
Aspect ratio	M				-																		
Corner shape	M					-																	
Object balance	S						-																
Perspective	S				M			-															
Use of grays	M	M						W	-														
Medium	M	S	W	M						-	M												
Texture details	S	M								M	-												
Stroke quality		S								S		-											
Use of light		S								W	W		-			M							
Contrast balance	M	S		M									S	-									
Color balance	M	S		M											-	W	W						
Contrast center					M								M	M		-	S						
Subject center					M									M		S	-						
Frame size			S															-			S		
Texture		S																	-			S	
Color		S		S																-			S
Matt size			S															S			-		
Texture		S																	S			-	
Color		S		S																S			-

Figure 11. Lower triangularized DSM for lowest level elements of artwork metric decomposition

At this point architectural concepts inevitably begin to come to mind. However, it is premature to begin architecture. Everything is influenced to some degree by adjacent systems. Step 5 identifies the impact of adjacent systems. In this case the physical layout of the gallery may be important. Figure 12 shows a metric decomposition of the gallery as an adjacent system. Two assessments must be made regarding the lowest level elements. First, will any of them influence our system goal? Second, does the architect have control over any of these elements?

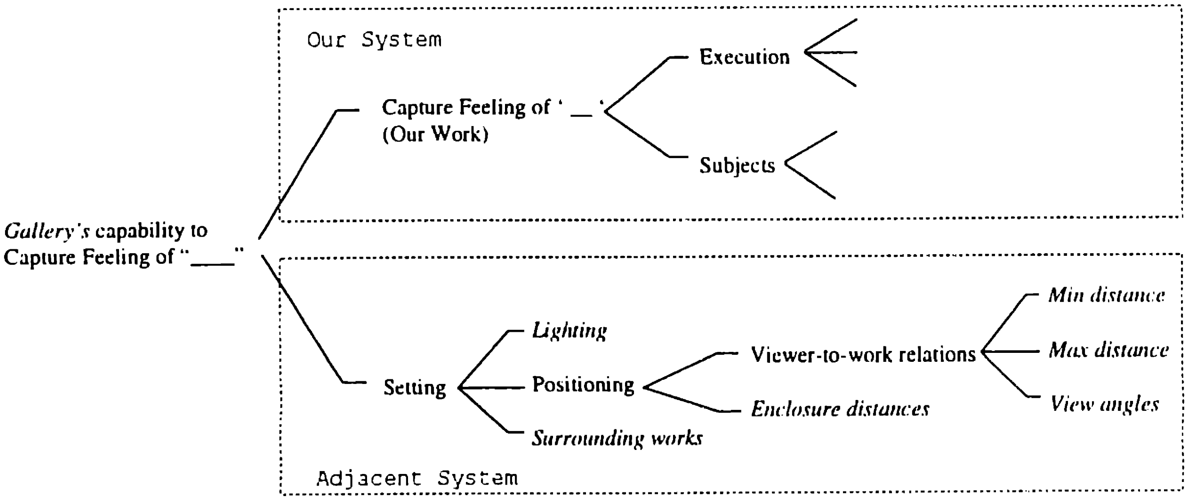

Figure 12. Adjacent system metric decomposition

The six adjacent system elements are added to the DSM from step 4 to make the new DSM in Figure 13. For this example let us assume that the architect has some control over the lighting but no control over the other elements[7]. After performing the DSM analysis say we find four of the six elements have influence and two do not. Figure 14 is the result of lower triangularizing Figure 13. An important result is seen. View angles moves to the first and most important decision. This is a correct result. As stated before metric decomposition is solution neutral. We have not made any statements as to weather the work is a painting, sculpture, or something in between. Available view angles govern this

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[7] Lighting is important. Warm incandescent light can negate the effect of a cool key color. The same is true of cool fluorescent light on warm key color works.

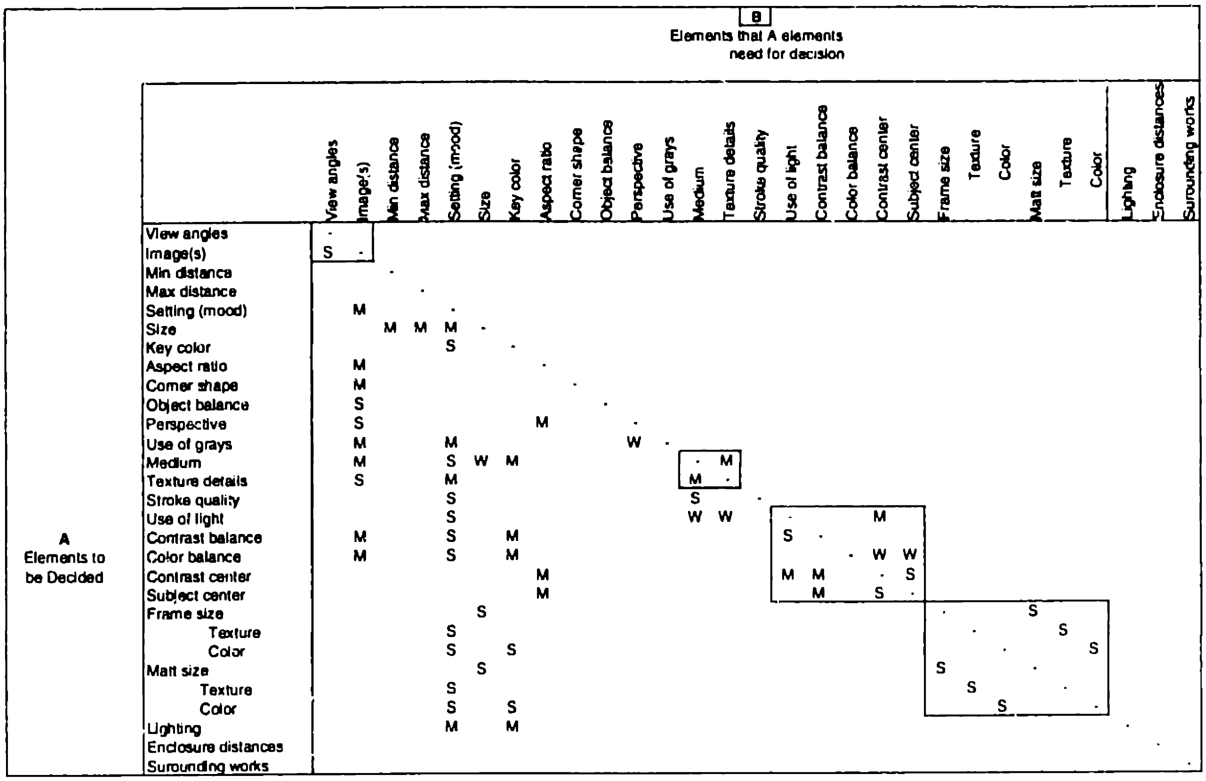
decision. If the artist is allowed 360 degree viewing of our work a sculpture may be the best medium. On the other hand if we are only allowed 180 degrees a painting might be better. If sculpture were selected all metric decomposition elements would remain. Only the wording would change. For example stroke quality would become surface finish and frame and matte would become base and decoration respectively.

B

Elements that A elements need for decision

A		Image(s)	Setting (mood)	Size	Key color	Aspect ratio	Corner shape	Object balance	Perspective	Use of grays	Medium	Texture details	Stroke quality	Use of light	Contrast balance	Color balance	Contrast center	Subject center	Frame size	Texture	Color	Matt size	Texture	Color	Lighting	Min distance	Max distance	View angles	Enclosure distances	Surounding works
Elements to be Decided	Image(s)	·																										S		
	Setting (mood)	M	·																											
	Size		M	·																						M	M			
	Key color		S		·																									
	Aspect ratio	M				·																								
	Corner shape	M					·																							
	Object balance	S						·																						
	Perspective	S				M			·																					
	Use of grays	M	M						W	·																				
	Medium	M	S	W	M						·	M																		
	Texture details	S	M								M	·																		
	Stroke quality		S								S		·																	
	Use of light		S								W	W		·			M													
	Contrast balance	M	S		M									S	·															
	Color balance	M	S		M											·	W	W												
	Contrast center					M								M	M		·	S												
	Subject center					M									M		S	·												
	Frame size			S															·			S								
	Texture		S																	·			S							
	Color		S		S																·			S						
	Matt size			S															S			·								
	Texture		S																	S			·							
	Color		S		S																S			·						
	Lighting		M		M																				·					
	Min distance																									·				
	Max distance																										·			
	View angles																											·		
	Enclosure distances																												·	
	Surounding works																													·

Figure 13. DSM for lowest level elements including adjacent systems



B
Elements that A elements need for decision

A
Elements to be Decided

	View angles	Image(s)	Min distance	Max distance	Setting (mood)	Size	Key color	Aspect ratio	Corner shape	Object balance	Perspective	Use of grays	Medium	Texture details	Stroke quality	Use of light	Contrast balance	Color balance	Contrast center	Subject center	Frame size	Texture	Color	Matt size	Texture	Color	Lighting	Enclosure distances	Surrounding works
View angles	·																												
Image(s)	S	·																											
Min distance			·																										
Max distance				·																									
Setting (mood)		M			·																								
Size			M	M	M	·																							
Key color					S		·																						
Aspect ratio		M						·																					
Corner shape		M							·																				
Object balance		S								·																			
Perspective		S						M			·																		
Use of grays		M			M						W	·																	
Medium		M			S	W	M						·	M															
Texture details		S			M								M	·															
Stroke quality					S								S		·														
Use of light					S								W	W		·			M										
Contrast balance		M			S		M									S	·												
Color balance		M			S		M											·	W	W									
Contrast center								M								M	M		·	S									
Subject center								M									M		S	·									
Frame size						S															·			S					
Texture					S																	·			S				
Color					S		S																·			S			
Matt size						S															S			·					
Texture					S																	S			·				
Color					S		S																S			·			
Lighting					M		M																				·		
Enclosure distances																												·	
Surrounding works																													·

Figure 14. Lower triangularized DSM for lowest level elements including adjacent systems

Upon completion of step 5 we have the entire design space mapped out and functionally connected. Step 6 places limits as to how far one can move each element. Numerous quantifiable limits are needed before conceptualization can begin. How big is the gallery space? What colors do we have to choose from? What mediums can we effectively work in? All of these constraints must be listed before conceptualization. The list is used as a check later in steps 7 and 8 to ensure a concept does not mature before we find it has violated some constraint. One of Buckminster Fuller's principles states 'you should work with forces and not against them'. Restated you could say work with constraints not against them. This philosophy can be seen in interior design where architects dress up duct work and plumbing of old buildings and make them integral parts of renovated interiors.

Step 7 sensitivity analysis has a quantifiable result for numerical problems. For non-numerical examples it is best accomplished by looking at the DSM in step 5 and list of constraints in step 6. The sculpture vs. painting decision can make a huge difference in our top level goal. If three dimensional confusion were the feeling to be captured a sculpture may have significant advantages over a painting. However, there might be a constraint identified in step 6 that eliminates sculpture as a possibility. These are the kinds of inspections that will start to lead the artist towards feasible concepts.

Step 8 begins the traditional architectural process. Many architects start here and have to identify and organize all the information found in steps one through seven as concepts evolve. Confusion and or one track mindedness often results. The saying 'you can't see the forest through the trees' is appropriate in such a situation. If the architect can not identify and organize upstream influences, the equivalent of the forest, he or she will never be able to take advantage of the natural structure of the problem.

Example 2. Needle Floating on Water

If you take an ordinary sewing needle and place it very carefully on the surface of water, it will float. Water surface tension is sufficient to support the needle despite its density being far greater than the water. If you were given the task of placing a needle on the water without using your hand, for minimum cost and complexity, how would you do it? The ESM method opens up the design space beyond initial thoughts so as to find best solutions. This example also shows how alternate decompositions can lead to the same answer.

Figure 15 lists the goal set. The metric and units still need to be identified in objective metrics. Determining if the objective has been met is evaluated by the metric and units. The metric decomposition shown in Figure 16 is based on force balance principles. Level 2 consists of the forces present in or possibly added to the system. The best solution will have to combine and or modify these forces. Level 3 decomposes the gravity into the mass of the needle and the earth's gravitational constant. Since the needle size, weight, and shape are a given and flying this experiment on the space shuttle will surely not be the lowest cost and complexity solution, this branch can not be decomposed further. Dynamic forces are zero because the needle has no velocity in the final state so this branch was not decomposed further. Magnetic forces are not naturally present. However, maybe some manipulation of magnetic properties could work. Similarly pneumatic pressure could possibly be changed to as part of the solution.

Goal Set
Floating Needle

Goal	Float needle on water
Metric Type	Objective
Metric	Exposed needle
Units	Square inches
Objective	Achieve objective for minimum cost and complexity

Figure 15. Goal set for floating needle problem

Modifying hydrodynamic properties of the water intuitively appears to be a fruitful path. Level 3 separates the three types hydrodynamic forces. Level four decomposes each further. Dynamic pressure is zero in the steady state but could be non-zero during needle "placement". Displacement forces are a function of the relative densities of the needle and water. Viscous forces are a function of a water surface tension parameter and needle surface roughness. Surface roughness is a given so this is a lowest level element. Level 5 decomposes the water and needle densities and the water surface tension. This is the lowest level to which the decomposition can go. The results suggest modification of water temperature or pressure. By now one should see that freezing the water first, dropping the needle on the ice by any simple mechanical means, and then thawing the water is a simple solution to the problem. Experimentation has shown this to work. There may be solutions using magnetism or air pressure but proposed solutions have yet to be as elegant as the ice approach.

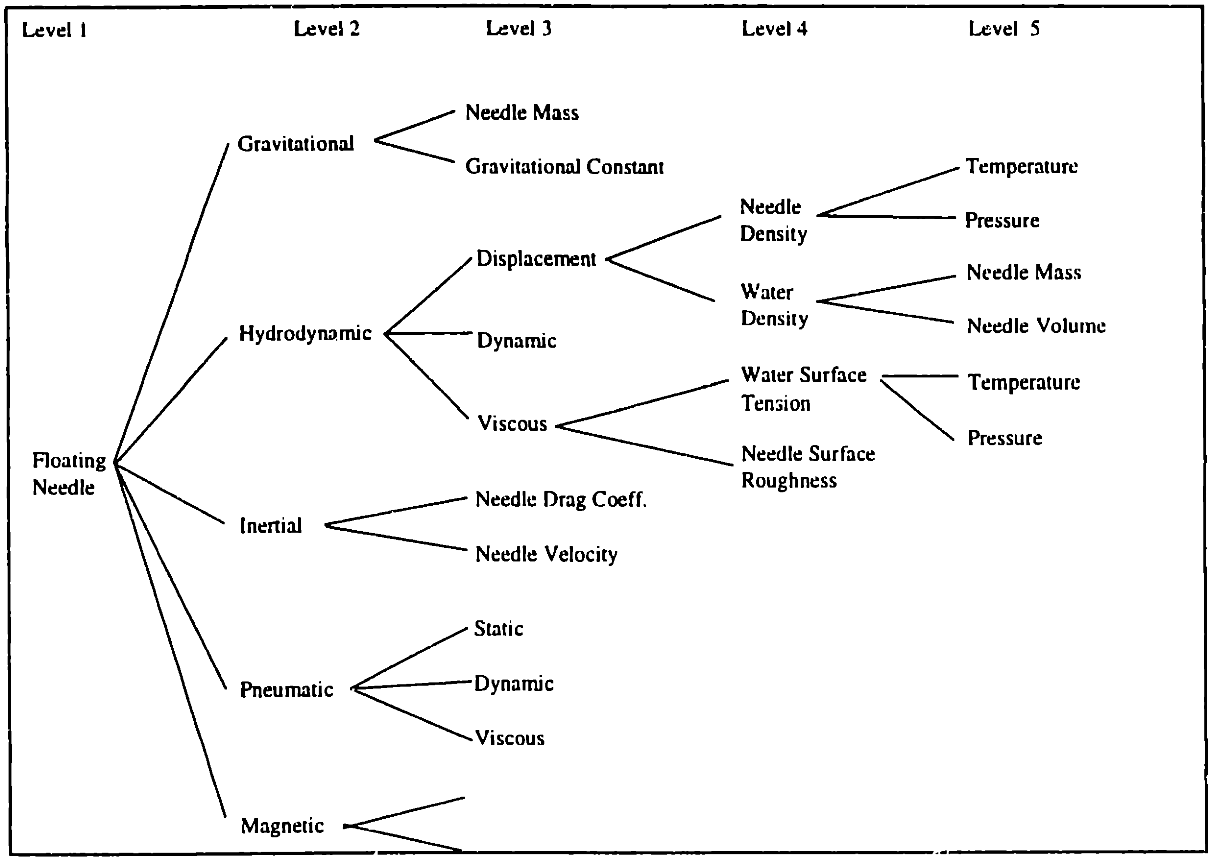


Figure 16. Floating needle metric decomposition

Metric decompositions are not unique. If one chooses a different set of heuristics would one arrive at the same solution? An architect with a different background might choose decomposition to this problem as shown in Figure 17. In this case the first decomposition is based on process. The needle and water can be brought together in one of two ways. Level 3 decomposition is based on a TRIZ design methodology introduced from Russia within the last few years. It says when faced with a problem look at changing the chemical phase of the materials involved. Although not as obvious in this decomposition, the suggestion of changing the water phase from liquid to solid is evident.

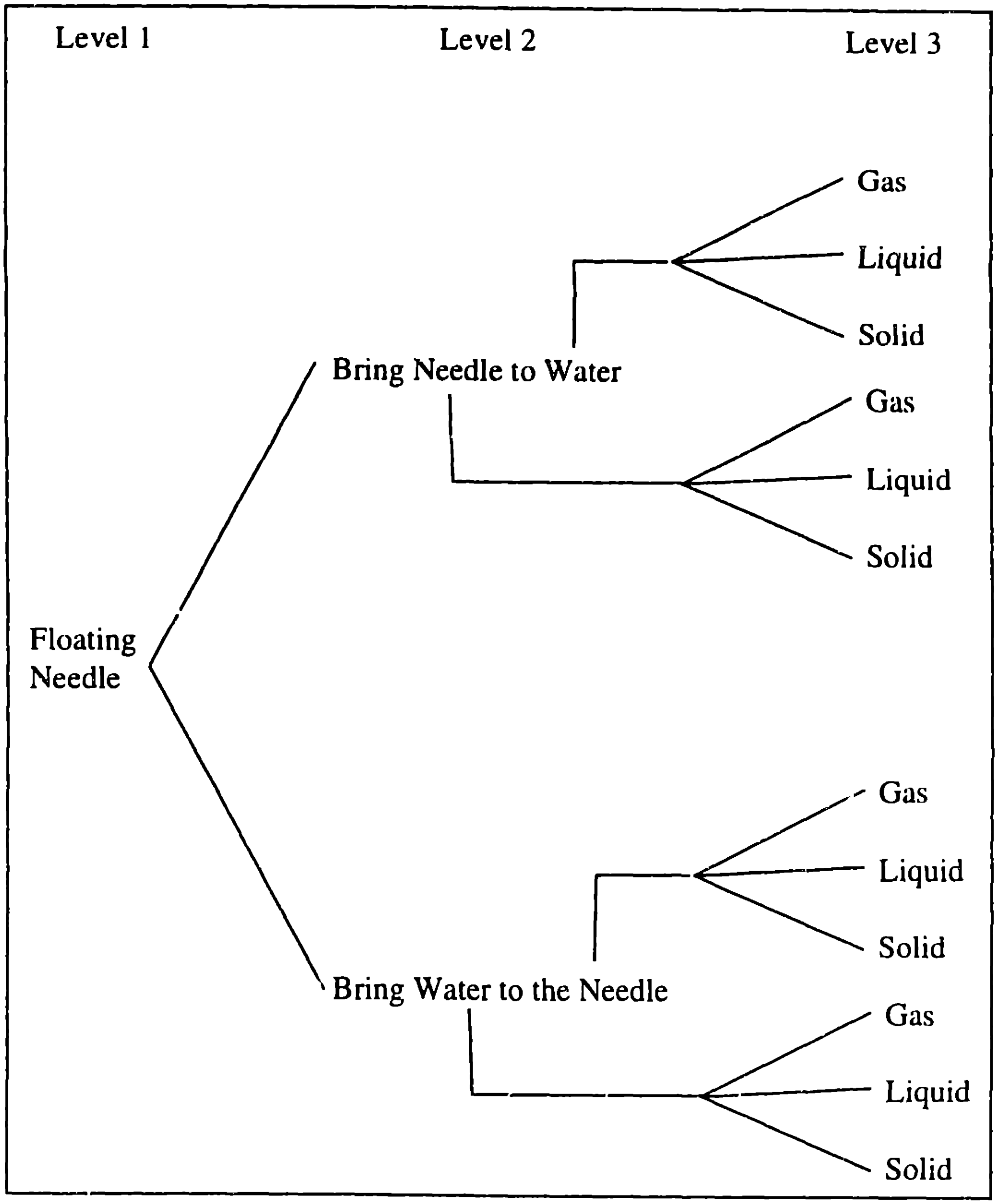


Figure 17. Alternate floating needle metric decomposition

Decompositions by other architects may not suggest any good concepts. If so the architect should simply keep trying different heuristics to decompose the problem. As stated in principle 5, architectural design methods *help* the creator conceive of solutions. It is up to the talent of the creator to use the methods effectively.

Example 3. Business Meeting Table

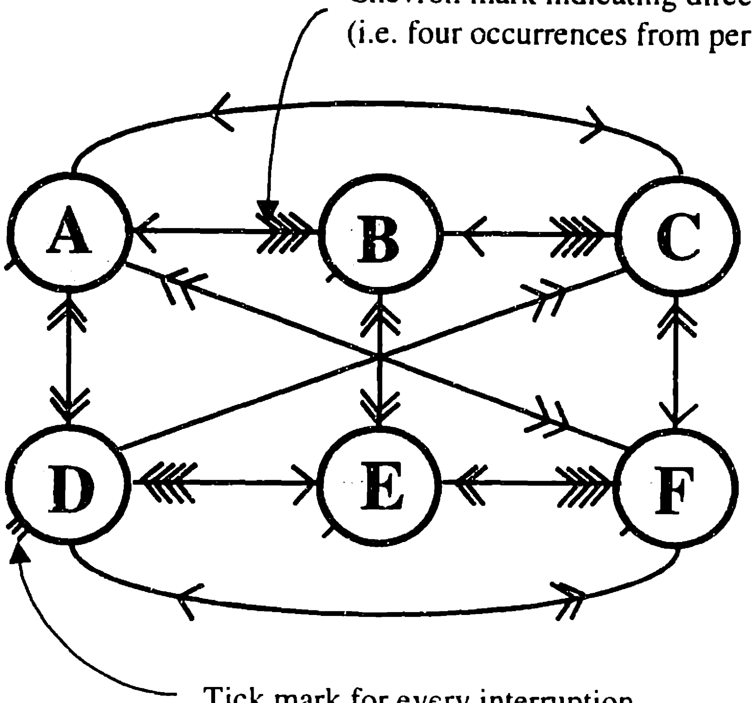
Working with chunks and mental integration of functional relationships are two useful architectural synthesis techniques. These can be effectively applied within the ESM method. Chunking is a means of simplifying a problem by aggregating like elements. The architect's problem is simplified by the reduction of elements. Mental integration of relationships is a technique to locate the optimum point between conflicting parameters.

When people sit down at a table for a meeting there is a surprisingly large number of social dynamics at work, all of which have some influence on the meetings effectiveness. If the table designer can understand the breadth and interactions of these dynamics, better table designs can be made.

The goal is to increase meeting effectiveness. This raises an obvious question "how do you measure effectiveness?" There are a variety of answers. So more information is needed and as an architect you have to continually question your client until the goal is clear. Let us say the goal of the table will be to improve brainstorming. The metric type, metric, units, and objective function would respectively be numerical, ideas generated, number there of, and maximization. Although a feasible goal set it does not work very well. A metric decomposition ends one level down. All you have are various table designs that would need experimental evaluation.

The architect should look for a goal metric that is readily decomposable by heuristics or principles. The dynamics of social interaction are often measured by sociograms. These are interaction maps between people in social situations. The units of measurement are occurrences which are how many times someone speaks to another. Figure 18 shows a typical map and the meanings of the markings. There is an architectural design principle that states "be careful who you invite to the first meeting because their background and biases will set the design". In order to have the most ideas put on the table it is best to have a wide variety of view points present. Getting the people to the table is the first step.

The next step is to have each participant be involved. The more involved each participant the more effective the meeting. Involvement can be measured by a sociogram. An improved goal set is shown in Figure 19. A good first cut at the objective function is to strive for balance. This would indicate equal participation. A secondary objective would be to maximize occurrences but not at the expense of balance.



Chevron mark indicating direction of occurrence
(i.e. four occurrences from person A to person B)

Tick mark for every interruption
(i.e. person D interrupts three times)

Figure 18. Typical sociogram map of verbal interactions

Goal Set
Meeting Table Design

Goal	Increase meeting effectiveness
Metric Type	Numerical
Metric	Sociogram
Units	Occurrences
Objective	Balanced sociogram

Figure 19. Goal set for meeting table design

As shown in Figure 20 the metric decomposition flows nicely from this goal. Seats make a logical decomposition in level 2. Given that the units are occurrences the question is what increases occurrences? Primarily three things affect participation. First someone has to receive enough visual and audio input in order to respond. Given adequate input one has to feel socially comfortable to participate. Assuming political, educational, and other cultural factors among participants are essentially equal, there are relative location dynamics that affect social comfort. Physical comfort is also important. Chairs, (if there are any, remember solution neutral) that are very uncomfortable will certainly detract form meeting effectiveness. Conversely if super comfortable reclining leather chairs are selected everyone will probably fall asleep!

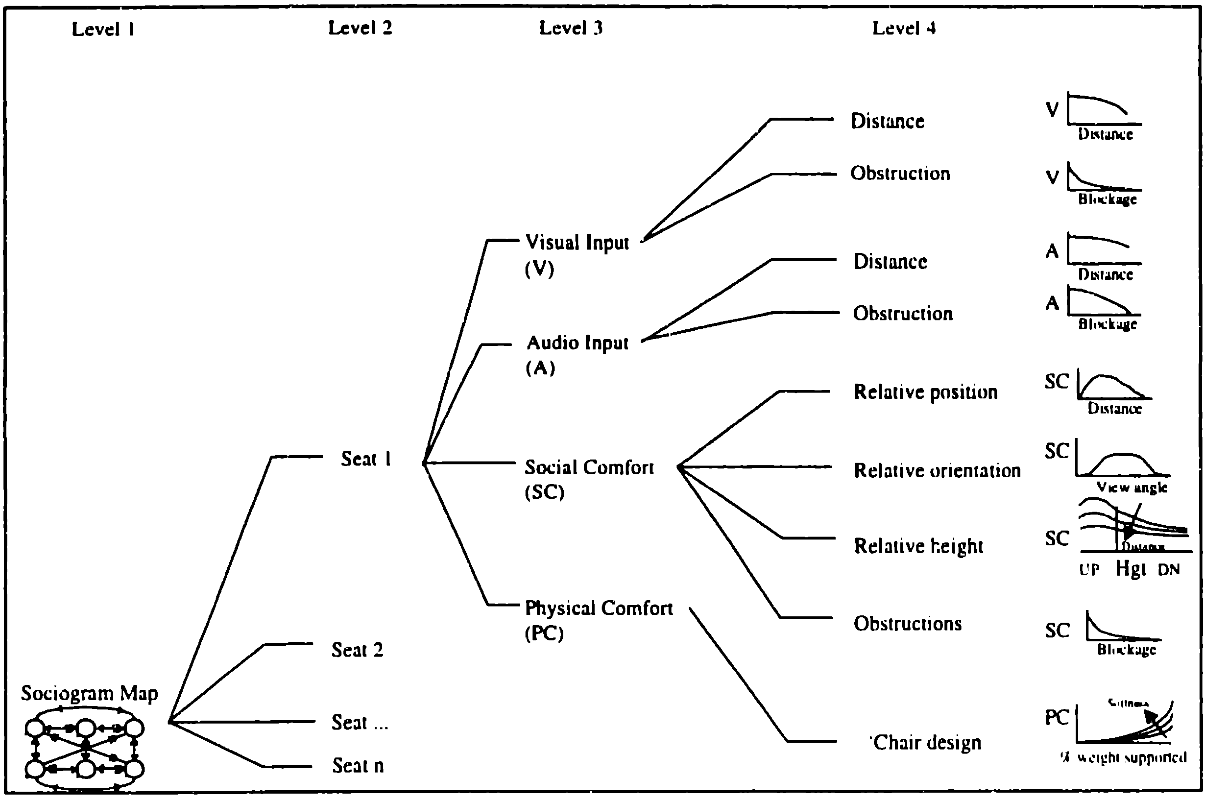


Figure 20. Meeting table design metric decomposition

The four elements decomposed in level 4. These are lowest level elements over which the architect has control. Studies have shown how each of these elements affect communication. In general these relationships are quite non-linear and sometimes a function of two or more variables. Such data is best presented graphically. A notional relationship is shown for each element. You can see how large and complicated the metric decomposition would become if every seat location were decomposed. Fortunately, by choosing seats as the first decomposition principle the architect can abstract decomposition levels three and four to every seat.

Before discussing the chunks and graphical data a quick look at step 3, boundary identification is needed (Figure 21). The table is one piece of all the furniture and equipment in the room. Each piece as well as the room design, heating, cooling and other attributes can significantly affect the real metric of interest, enhanced communication. For purposes of the example we will say the designer only has control over the table.

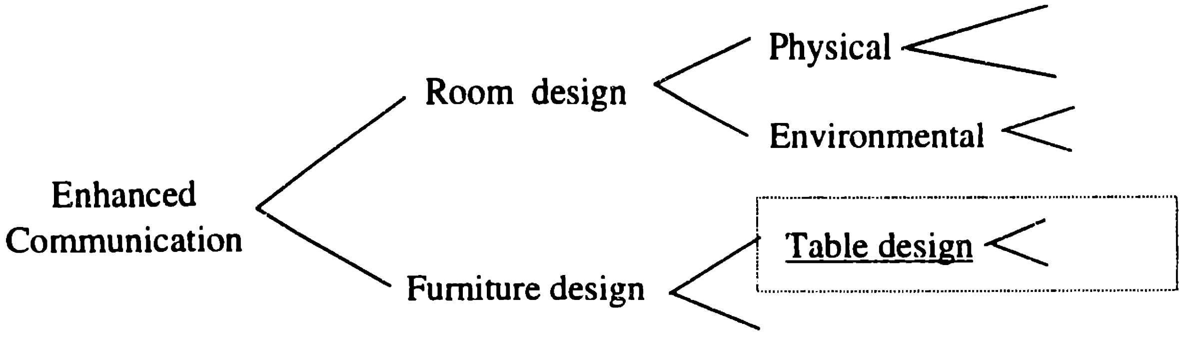
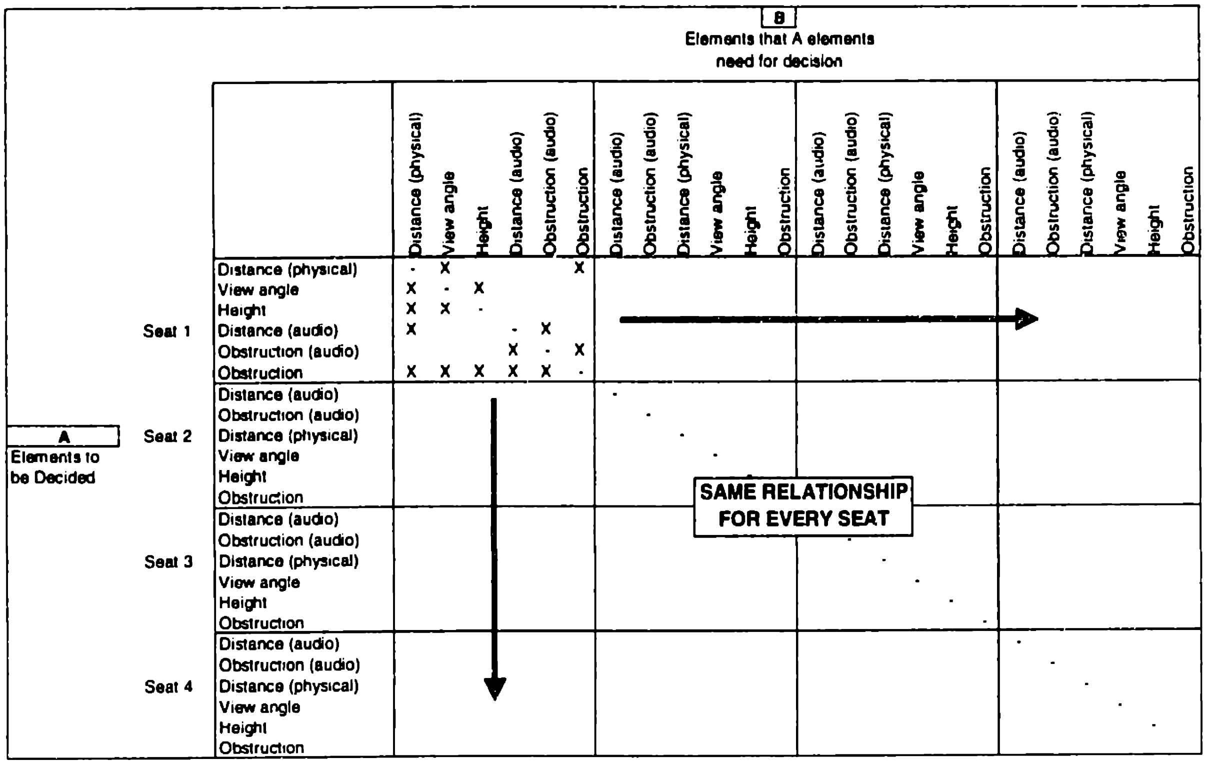


Figure 21. Expanded upper boundary of meeting table design goal

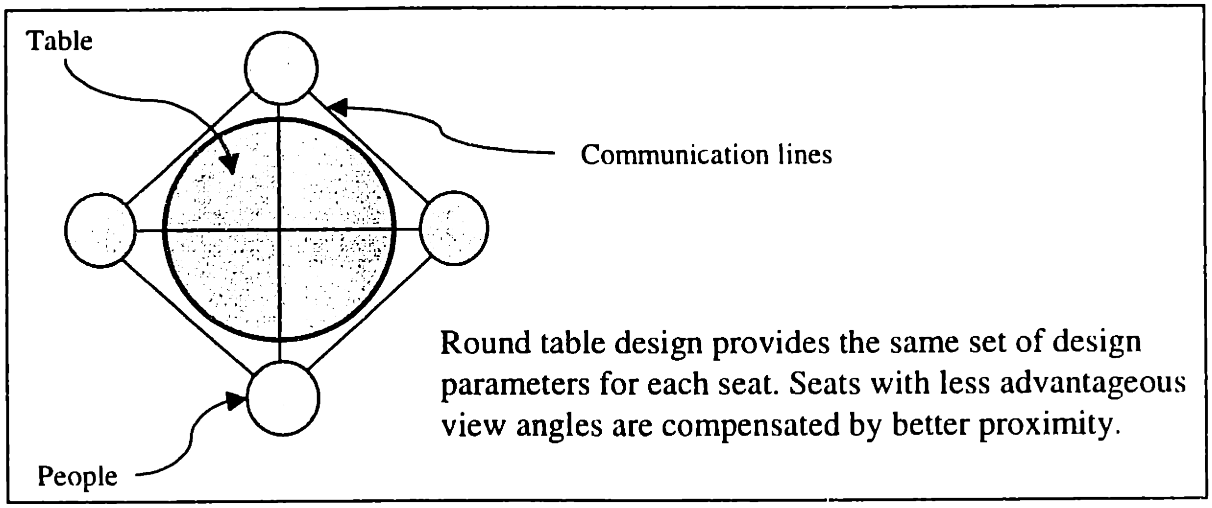
Step 4 identifies all the functional and iterative connections between lowest level elements. A DSM inclusive of every element for every seat would be huge. However, by inspection and mental integration of the graphical data the architect can eliminate some elements because they are insignificant relative to others. For example studies might show physical chair comfort has little influence on occurrences relative to social comfort, visual and audio. If so the entire chair branch can be eliminated from the DSM in step 4. Similarly if occurrences as a function of visual input is nearly constant for the distances of interest then it too can be neglected.

Figure 22 shows the simplified lower triangularized DSM. Here the value of chunking becomes apparent. The submatrix at every seat intersection has the same set of relationships. Therefore the designer can look at every intersection as a chunk and make decisions by chunk. This works particularly well here. A balanced sociogram is desired. Therefore the net result of the design parameters, distance, view angle, etc should be the same for each seat. The best geometry to facilitate equal participation is a circle as shown in Figure 23. A person's view angle to each other person is greater the closer the other person is. Greater view angles reduce social comfort. However, closer proximity increases social comfort. The two dominant effects compensate each other and create a nearly equal social comfort level for every person relative to every other. A circular table is well known for its equalization qualities. By using ESM the benefits of a circular table become apparent.



		Distance (physical)	View angle	Height	Distance (audio)	Obstruction (audio)	Obstruction	Distance (audio)	Obstruction (audio)	Distance (physical)	View angle	Height	Obstruction	Distance (audio)	Obstruction (audio)	Distance (physical)	View angle	Height	Obstruction	Distance (audio)	Obstruction (audio)	Distance (physical)	View angle	Height	Obstruction
	Distance (physical)	-	X				X																		
	View angle	X	-	X																					
	Height	X	X	-																					
Seat 1	Distance (audio)	X			-	X																			
	Obstruction (audio)				X	-	X																		
	Obstruction	X	X	X	X	X	-																		
	Distance (audio)							-																	
	Obstruction (audio)								-																
Seat 2	Distance (physical)									-															
	View angle										-														
	Height											-													
	Obstruction												-												
	Distance (audio)													-											
	Obstruction (audio)														-										
Seat 3	Distance (physical)															-									
	View angle																-								
	Height																	-							
	Obstruction																		-						
	Distance (audio)																			-					
	Obstruction (audio)																				-				
Seat 4	Distance (physical)																					-			
	View angle																						-		
	Height																							-	
	Obstruction																								-

Figure 22. Lower triangularized DSM for meeting table design lowest level elements



Round table design provides the same set of design parameters for each seat. Seats with less advantageous view angles are compensated by better proximity.

Figure 23. Round meeting table design for a balanced sociogram

Step 3 identified the room and other furniture as significant adjacent systems. For this example lighting and background noise were added as significant elements over which the designer has no control. These two elements were incorporated into the DSM per step 5 (Figure 24).

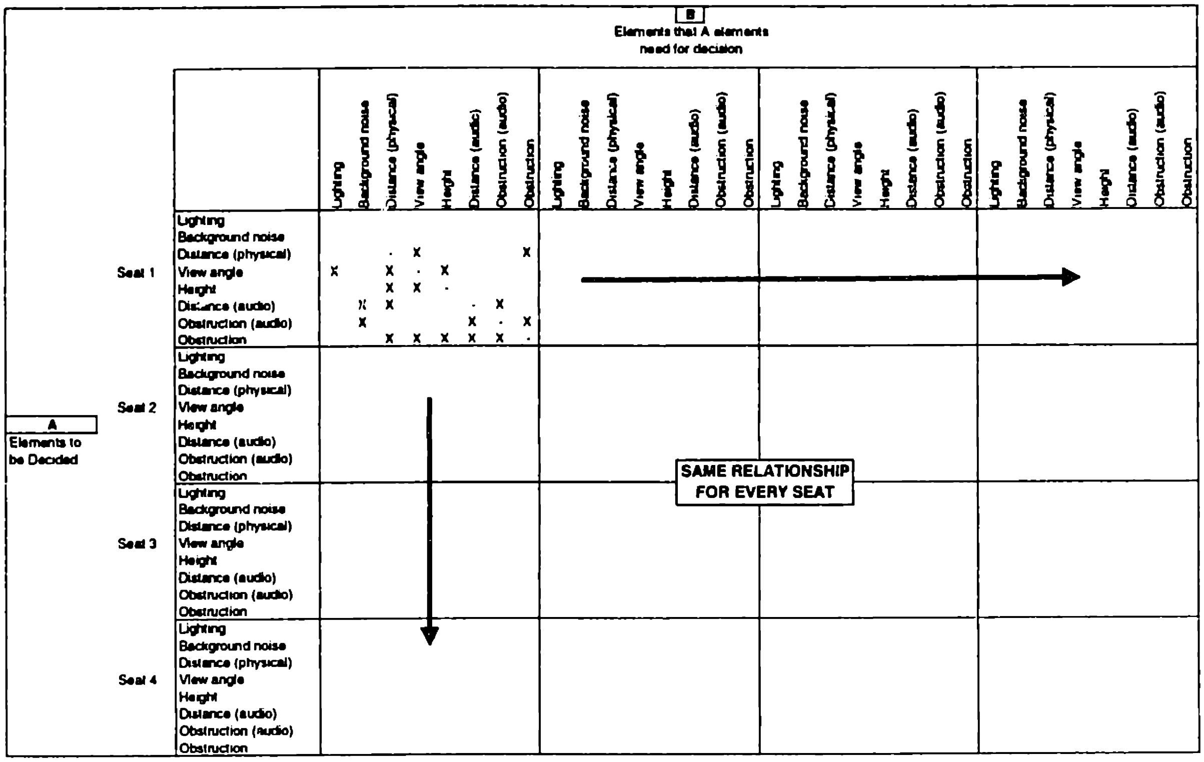


Figure 24. Lower triangularized DSM for meeting table design including adjacent systems' lowest level elements

The task then becomes how to maximize total occurrences. Obviously if there are more seats there will be more occurrences. But by looking at the relationships we see that if the table gets too big due to a large number of seats total occurrences will go down because of the large distances created.

A designer comfortable with numerical analyses and confident in the comprehensiveness of the system elements could develop a computer program to calculate total occurrences as a function of seat number and design parameters. An optimum size and possibly a variation of a circle would be found. More than likely there will be elements and other intangibles involved in the final architecture selection that will temper the numerical outcome. For this reason this example is really semi-numerical.

Example 4. New Product Architecture

The elements of this example are familiar to many. Since the goal is to make money product architecture can be numerically measured.

The goal set is given in Figure 25. The key to form independence is the goal statement. If a specific product was identified the design space would immediately become restricted. Net present value (NPV) is a common measure of financial performance. It is not always the most appropriate but is a good one for identifying the entire design space. Units and objective function follow naturally from the metric.

Goal Set
New Product Architecture

Goal	Successful new product design
Metric Type	Numerical
Metric	Discounted future value (NPV)
Units	Dollars
Objective	Maximize NPV

Figure 25 Goal set for new product architecture

The NPV metric decomposition is shown in Figure 26. Even without a concept it is rather complicated. Because the goal is numerical this is a true metric decomposition. Unit consistency can be tracked for every branch. Decomposition levels are more straight forward for numerical trees. Since every element is a numerical function of its sub elements you can simply list sub elements as the next level. For example NPV is comprised of only four things, time, income stream, expense stream, and a discount factor to account for risk and time value of money. Likewise expenses are a familiar aggregate of development, variable, and fixed costs. Some functions are well understood by their constituents but not in form. Market size prediction, (quantity) is a classic example. Formulations based on economic principles have limited applicability. Subelement interactions are very complicated and most importantly a function of the product category. Therefore "text book" derivations are of little practical value. Good forecasts are usually based on parametric models.

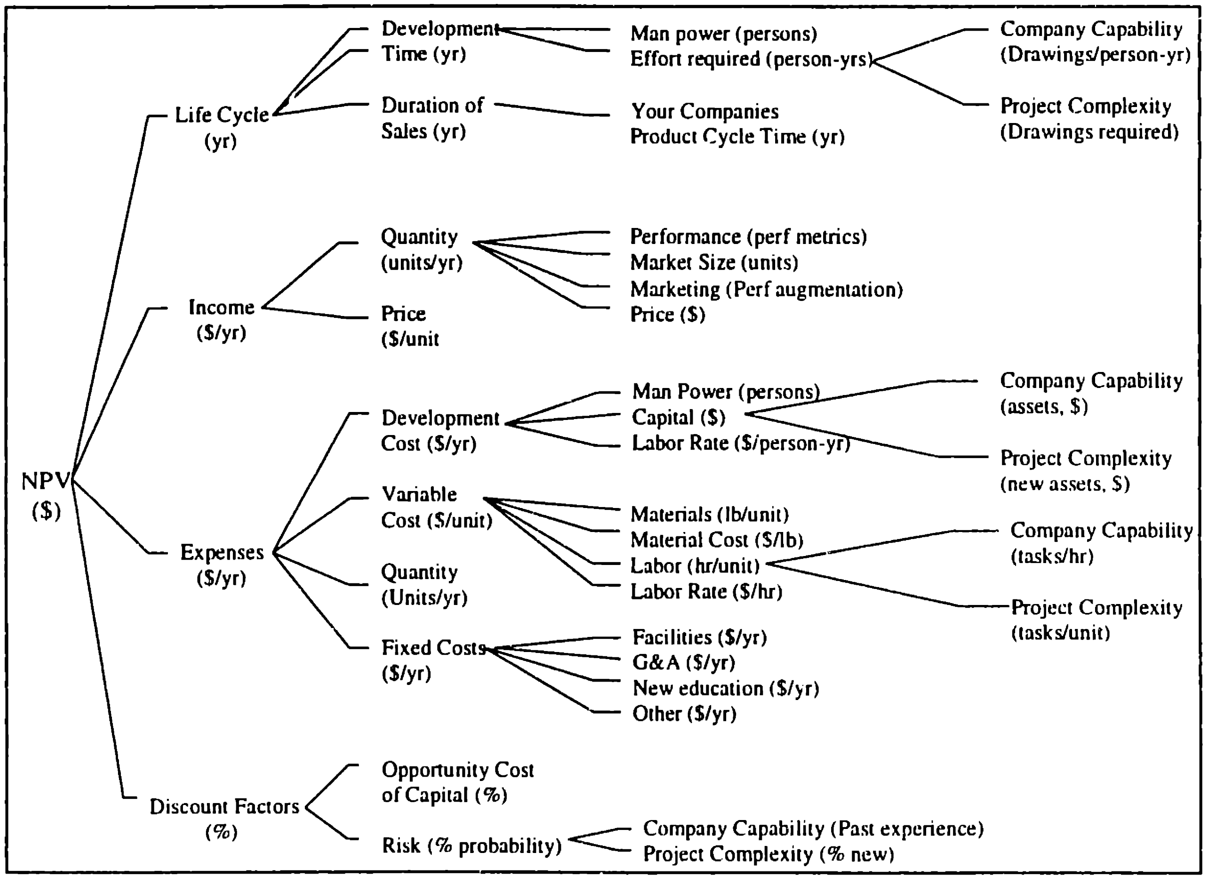


Figure 26. Metric decomposition for a new product architecture

Per the metric decomposition method each branch terminated when a concept was required or the element was not under the architect's control. In this case all lowest level elements are controllable.

The lowest level elements show a lot of overlap. Company capability and project complexity each appear four times. Debatably "your companies product cycle time" could also be a function of company capability and project complexity. These two elements are the most difficult to quantify. All of the other lowest elements are relatively easy to quantify. From my experience company capability and project complexity are also the most influential on NPV. Many times the decision to go forward rests on your assessment of "can we do it". Company capability and project complexity can not be assessed in the absence of the other. "Complexity is a relative thing" as stated in Reference 4. A product that is complex for one company may not be for another. Relative complexity is how complex the subject is in light of a capability. Unfortunately relative complexity assessments are often made intuitively and incorrectly. One only has to look at the dismal record of project performance. Well over 90% of all projects finish behind schedule and over budget. A substantial percentage of projects are over by factors of two. In almost every case a poor assessment of relative complexity was made. Either absolute complexity was under assessed, capability was over assessed, or both. This topic is ripe for research. If someone could develop robust quantifiable relative complexity methods it would dovetail very well with the ESM method. Such a method is important because it drives so many upper elements.

Examination of the upper boundary poses some interesting questions for the architect. For this example company strategy would be the next level up (Figure 27). The goal of the company is to maximize the sum of all projects NPVs. The product manager, who is part of the company system, has to decide to optimize on the criteria set in step 1 or work towards a new goal of maximum company NPV as part of the company strategy metric. This can be a difficult question. Adjoining systems need to be identified in this particular case. The contributions of each system to the company strategy, and their interactions must be understood. It is conceivable that our system goal may not be to make money, but to gain market share at a financial loss. This would be done in order to increase NPV of an adjacent system. Social, legal, and other systems that feed into company strategy could affect our system goals. So even before you get to step 5 you can see an iterative loop develop. For this case we can assume the NPV maximization goal is appropriate.

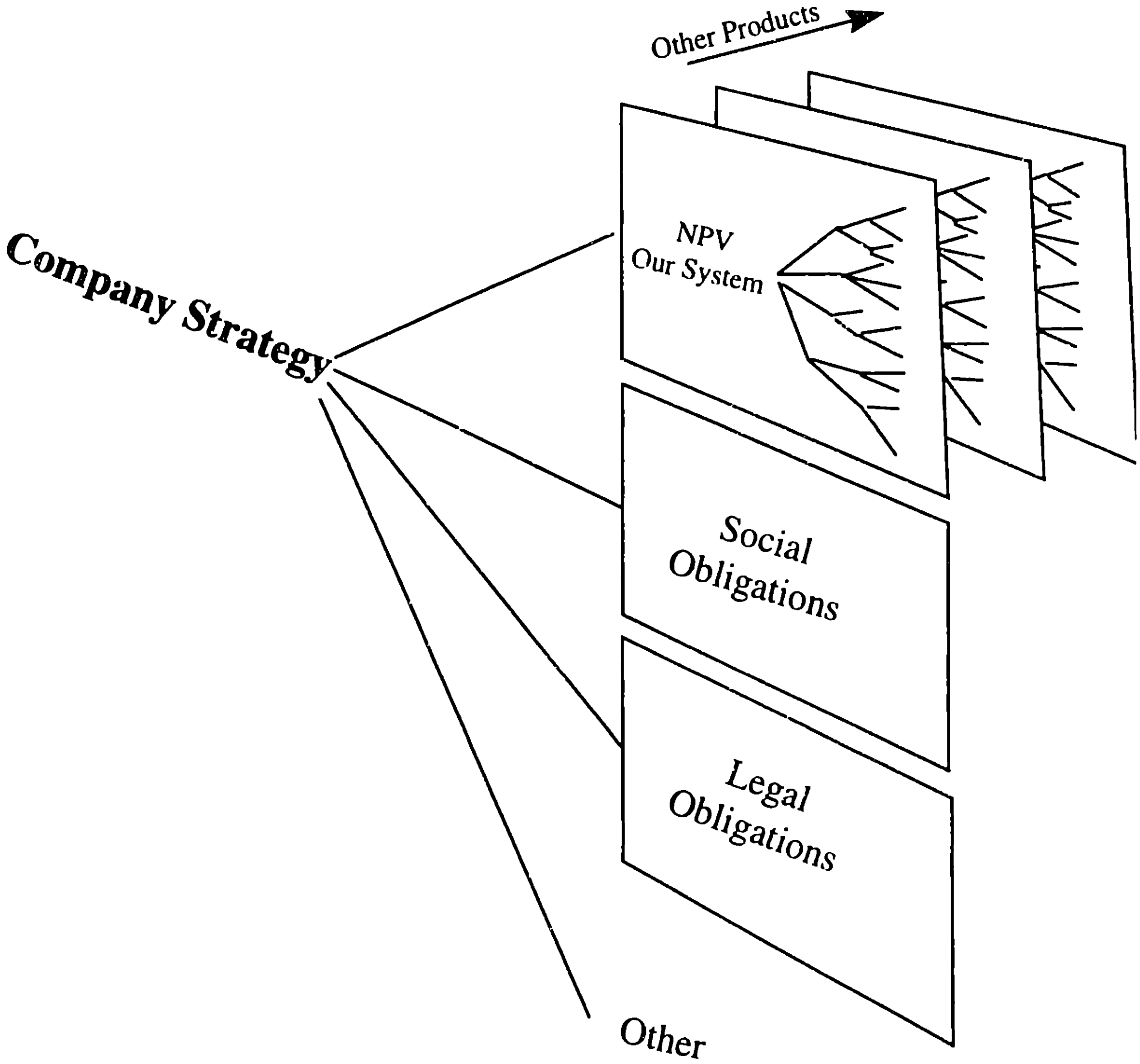


Figure 27. Next level up and adjacent systems to new product goal

The DSM performed in step 4 shows significant couplings in the up front decisions. Figure 28 shows the raw DSM results and Figure 29 shows the lower triangularized version.

Selection of performance levels and new assets required to execute the project are functions of each other. Both of these elements are functionally composed of other elements so the resulting iteration box is relatively large.

CC = Company Capability
PC = Project Complexity

B
Elements that A elements need for decision

A
Elements to be Decided

	Man power	CC (Dwgs/person-yr)	PC (Dwgs req)	Company's cycle time	Product performance	Market size	Marketing	Price	CC (assets)	PC (new assets)	Labor rate (development)	Material costs	CC (tasks/hr)	PC (tasks req/unit)	Labor rate (production)	Facilities	G&A	New education	Other	Opportunity costs	CC (past experience)	PC (% new)
Man power	-	X							X	X						X					X	
CC (Dwgs/person-yr)		•							X	X						X		X			X	
PC (Dwgs req)			-		X				X	X				X							X	X
Company's cycle time	X	X	X	-						X											X	X
Product performance					•			X[1]	X	X						X		X			X	
Market size					X	-	X	X		X											X	X
Marketing					X	X	-		X									X			X	X
Price					X		X	-														X
CC (assets)									•												X	
PC (new assets)			X		X				X	•				X		X		X				
Labor rate (development)		X	X		X					X	-							X			X	
Material costs					X							•									X	
CC (tasks/hr)									X				•								X	
PC (tasks req/unit)			X		X				X	X				•							X	X
Labor rate (production)										X			X		-			X			X	
Facilities	X				X				X	X						•					X	
G&A	X																-				X	
New education					X[2]					X								•			X	
Other																			-		X	
Opportunity costs				X						X	X	X			X	X	X	X	X	-	X	
CC (past experience)																				X	-	
PC (% new)			X		X																	-

Figure 28 DSM for a new product architecture

CC = Company Capability
PC = Project Complexity

B
Elements that A elements need for decision

A
Elements to be Decided

	CC (past experience)	Product performance	PC (new assets)	New education	CC (assets)	Facilities	PC (Dwgs req)	PC (tasks req/unit)	Man power	PC (% new)	CC (Dwgs/person-yr)	Company's cycle time	Labor rate (development)	Material costs	CC (tasks/hr)	Labor rate (production)	G&A	Other	Marketing	Price	Opportunity costs	Market size
CC (past experience)	-																					
Product performance	X	-			X	X														X		
PC (new assets)		X	·	X	X	X	X	X														
New education	X	X	X	·																		
CC (assets)	X				-																	
Facilities	X	X	X		X	·			X													
PC (Dwgs req)	X	X	X		X		-	X		X												
PC (tasks req/unit)	X	X	X		X		X	-		X												
Man power	X		X		X	X			-		X											
PC (% new)	X	X					X			-												
CC (Dwgs/person-yr)	X		X	X	X	X					-											
Company's cycle time	X		X				X		X	X	X	-										
Labor rate (development)	X	X	X	X			X				X		-									
Material costs	X	X												-								
CC (tasks/hr)	X				X										·							
Labor rate (production)	X		X	X											X	·						
G&A	X								X								-					
Other	X																	·				
Marketing	X	X		X	X					X									-			X
Price		X								X									X	-		
Opportunity costs	X		X	X		X						X	X	X		X	X	X			-	
Market size	X	X	X							X									X	X		-

Figure 29. Lower triangularized DSM for new product architecture

A functional relationship was shown for the most general case. If there was any possibility of one element being a function of another it was indicated. Product performance is a function of price shown in the upper right of Figure 29 appears to be counter intuitive. However, some people perceive higher performance from higher priced products. Products like perfume, jewelry, and other very subjective based products show such negative elasticity. Marketing decisions can be influenced by market size. Small markets may dictate one kind of advertising and sales, a large market another, the impact of which may well be different between the two.

The significant adjoining systems identified in step 5 are other products and external environmental factors (Figures 30, and 31). To assess other product influences on our system fundamental questions need to be asked. For example is our product dependent upon the success of an adjoining product? If so should there be flexible architecture to accommodate its failure? The other aspect to question is “will any future adjoining systems be created by our system?” Platform products are a good example of such an occurrence. If our product is architected to be a core system then it will spawn many adjacent systems. This could be good or bad depending on company strategy.

CC = Company Capability
PC = Project Complexity

B
Elements that A elements need for decision

A
Elements to be Decided

	Man power	CC (Dwgs/person-yr)	PC (Dwgs req)	Company's cycle time	Product performance	Market size	Marketing	Price	CC (assets)	PC (new assets)	Labor rate (development)	Material costs	CC (tasks/hr)	PC (tasks req/unit)	Labor rate (production)	Facilities	G&A	New education	Other	Opportunity costs	CC (past experience)	PC (% new)	Competitors price	Competitors performance	General economy	Market labor rate (dev)	Market labor rate (prod)	Market material rates
Man power	·	X							X	X						X					X				X			
CC (Dwgs/person-yr)		·							X	X						X		X			X							
PC (Dwgs req)			·		X				X	X				X							X	X						
Company's cycle time	X	X	X	·						X											X	X						
Product performance					·			X	X	X						X		X			X			X				
Market size					X	·	X	X		X											X	X			X			
Marketing					X	X	·		X									X			X	X	X		X			
Price					X		X	·														X	X		X			
CC (assets)									·												X							
PC (new assets)			X		X				X	·				X		X		X										
Labor rate (development)		X	X		X					X	·							X			X					X		
Material costs					X							·									X							X
CC (tasks/hr)									X				·								X							
PC (tasks req/unit)			X		X				X	X				·							X	X						
Labor rate (production)										X			X		·			X			X						X	
Facilities	X				X				X	X						·					X							
G&A	X																·				X							
New education					X					X								·			X							
Other																			·		X							
Opportunity costs				X						X	X	X			X	X	X	X	X	·	X				X			
CC (past experience)																				X	·							
PC (% new)			X		X																	·						
Competitors price																							·					
Competitors performance																								·				
General economy																									·			
Market labor rate (dev)																										·		
Market labor rate (prod)																											·	
Market material rates																												·

Figure 30. DSM for a new product architecture including external factors

CC = Company Capability
PC = Project Complexity

B
Elements that A elements need for decision

A
Elements to be Decided

	CC (past experience)	Competitors performance	Product performance	PC (new assets)	New education	CC (assets)	Facilities	PC (Dwgs req)	General economy	PC (tasks req/unit)	Man power	Market labor rate (dev)	PC (% new)	CC (Dwgs/person-yr)	Market material rates	Company's cycle time	Labor rate (development)	Market labor rate (prod)	Material costs	CC (tasks/hr)	Labor rate (production)	G&A	Competitors price	Other	Marketing	Price	Opportunity costs	Market size
CC (past experience)	.																											
Competitors performance		.																										
Product performance	X	X	.			X	X																			X		
PC (new assets)			X	.	X	X	X	X		X																		
New education	X		X	X	.																							
CC (assets)	X					.																						
Facilities	X		X	X		X	-				X																	
PC (Dwgs req)	X		X	X		X		.		X			X															
General economy									.																			
PC (tasks req/unit)	X		X	X		X		X		.			X															
Man power	X			X		X	X		X		.			X														
Market labor rate (dev)												.																
PC (% new)	X		X					X					.															
CC (Dwgs/person-yr)	X			X	X	X	X							.														
Market material rates															.													
Company's cycle time	X			X				X			X		X	X		.												
Labor rate (development)	X		X	X	X			X				X		X			.											
Market labor rate (prod)																		.										
Material costs	X		X												X				.									
CC (tasks/hr)	X					X														.								
Labor rate (production)	X			X	X													X		X	.							
G&A	X										X											.						
Competitors price																							.					
Other	X																							.				
Marketing	X		X		X	X			X				X										X		.			X
Price			X						X				X										X		X	.		
Opportunity costs	X			X	X		X		X							X	X		X		X	X		X			-	
Market size	X		X	X					X				X												X	X		.

Figure 31. Lower triangularized DSM for new product architecture including external factors

Other products must include competitors' products as well. The quantity branch is significantly affected by competition. Global external environmental factors have profound influence on product system architecture. Usually the architect has no control over them. The general state of the economy, competitor price and performance, market rates for labor and materials are a few examples that must be included within the system boundary. Without these external influences a proper architecture can not be done. The ESM method clearly identifies internal and external influences and which ones the architect has control over. For this example we have assumed there are no significant products within our company and competitors products and the general economy are significant. The lower triangularized version of the final DSM shown in Figure 31 maintains essentially the same decision hierarchy as step four.

After examining Figure 31 and thinking about the product conceptualization process you can see an iterative loop develop between steps 5 and 8. Different system architectures have different sets up upstream influences. An architecture that requires no new assets, facilities, or education would be nearly uncoupled. This result substantiates the rule of thumb that new products that fit within the existing system are the most likely to be launched. If new assets are required iterations must be made to find the best levels of new assets, facilities, and education for each architecture evaluation. This makes the entire architectural process rather complicated. New technology products are always complicated by the requirement for new assets. The more upstream influences involved, the more complicated the architecture.

Example 5. Team Project.

This relatively simple example is taken from the author's own experience. It clearly illustrates how ESM helps the architect identify his or her own limits. A Sloan management class project required a team of students to make a change for the better on campus. Our group chose to reduce the amount of solid waste generated by the cafeteria. The metric decomposition shown in Figure 32 was created. It was interesting to note the consumer had only two direct means to reduce waste, eat less food or recycle more often. Getting the consumer to recycle more often was found to be a function of a number of elements.

In step 3 a team member noted that the goal was not quite right. Create less waste was correct but time had to be included in the top level metric. The architecture of the change process had to account for permanency. Otherwise closing the cafeteria for a day would be the best solution. So a new top level metric was formed and the area under the curve was to be maximized. The previous metric decomposition became the top branch of the new metric decomposition. It corresponded to the vertical axis of the goal graph. Time, the horizontal axis became first element of the new lower branch (Figure 33.)

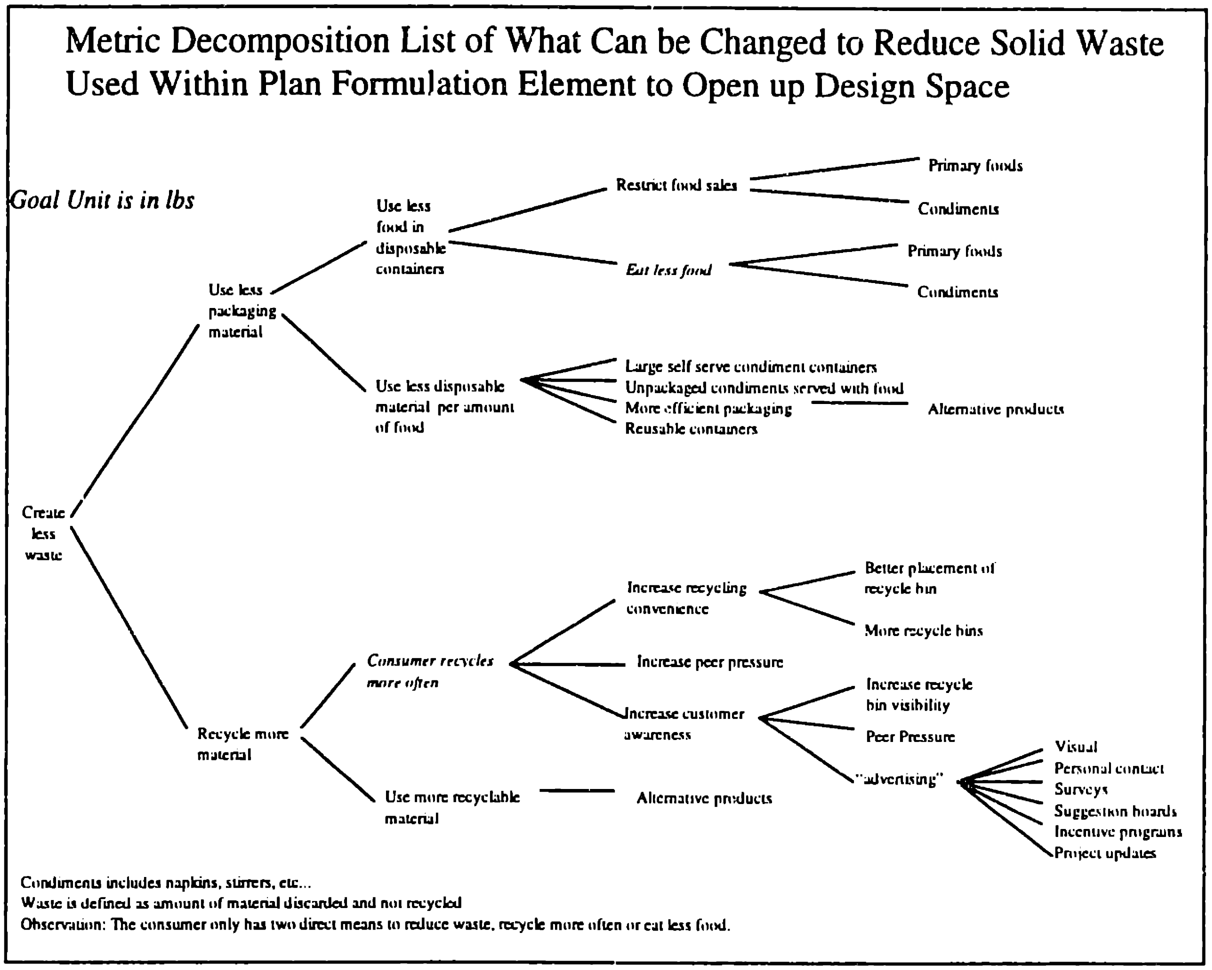


Figure 32. Metric decomposition of solid waste reduction project goal

At this point I got stuck. How do I make the changes permanent? Do the cascading elements after 'consumer recycles more often' guarantee permanency? Physical change can be undone if someone changes his or her mind. The answer lies in changing the mindset of the stakeholders involved. If cafeteria operators and consumers do not truly embrace a new way of thinking about the environment changes will not be permanent. How do I change people's mindsets? I did not know. It was clear that a co-architect steeped in social psychology was needed. One that could conceive of concepts that could work in concert with the upper branch. The architects would have to work together in steps 3 through 8 to determine the best architecture.

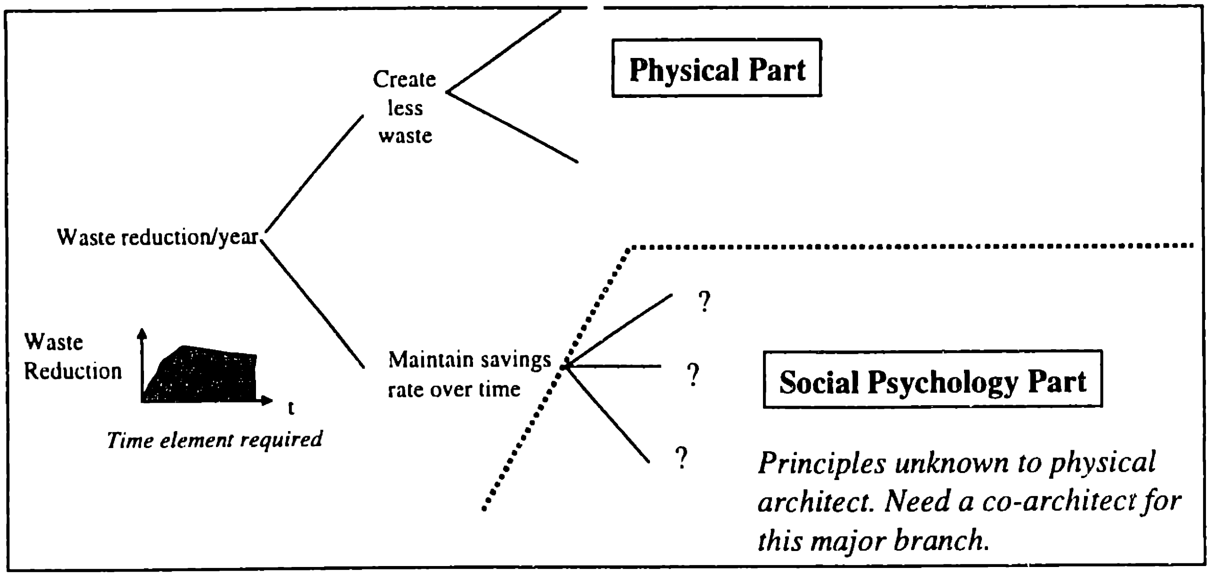


Figure 33. Major decomposition branch in need of a co-architect

The ESM method clearly identifies each architect's system and interfaces. ESM also quantifies the effect of each branch. If it had not been for goal set and metric decomposition charts the team member may not have identified the inappropriateness as early as she did or possibly at all.

Example 6. Thesis

Once the ESM method was established the task became one of communication to others. A multitude of formats could have been used. For example a single or multi case format, a step by step description, a textbook approach with proofs, descriptions, and examples, or even a highly graphical presentation were candidate formats. Since I had to 'design' the thesis document it was only appropriate that ESM be used.

My first goal set is shown on the left of Figure 34. The goal was a superior thesis measured by a letter grade metric. The objective function was to maximize the grade. A pretty common goal set. As I began metric decomposition the goal set started to bother me. What I was really looking for was favorable comments from my advisor and peers. If their comments were favorable I would be satisfied and a good grade would follow. The goal set was rewritten as shown in the right of Figure 34. The metric type changed to spiritual, which is the appropriate goal for educational endeavors.

	Initial Goal Set	**Improved Goal Set**
Goal	Superior thesis	Feel good about academic accomplishments
Metric Type	Objective	Spiritual
Metric	Grade	Satisfaction
Units	A, B, C...	A satisfaction utility
Objective	Get an A	Maximize personal satisfaction

Figure 34. Initial and improved goal sets for thesis design

The metric decomposition shown in Figure 35 flowed well after the change. Even though this is a spiritual metric type I chose to attach "units" to each element. This forces the architect to describe what each element really means. Level 2 decomposition is based on the four basic tensions of a project. Schedule was a constraint and not under my control so it was a lowest level element. Thesis performance decomposed well by needs, values, and facts, a principle taken from Reference 5. Cost was a function of time and not money. Time required was driven by the familiar orthogonal measurements of breadth and depth. The amount of research performed and the amount of validation further decomposed depth. Validation was seen as the application of research. The two together constituted depth. Cost was also a function of favors I would need. Partial reviews and proof reading would be needed. I knew only so many favors could be had so I would have to spend them wisely. Since risk could not be quantified it was evaluated subjectively through out the process. Therefore needs, values, and facts were made the focus of my document design. The objective of each branch is to get agreement. If one agrees with the data presented for each branch then one agrees that the ESM method is credible.

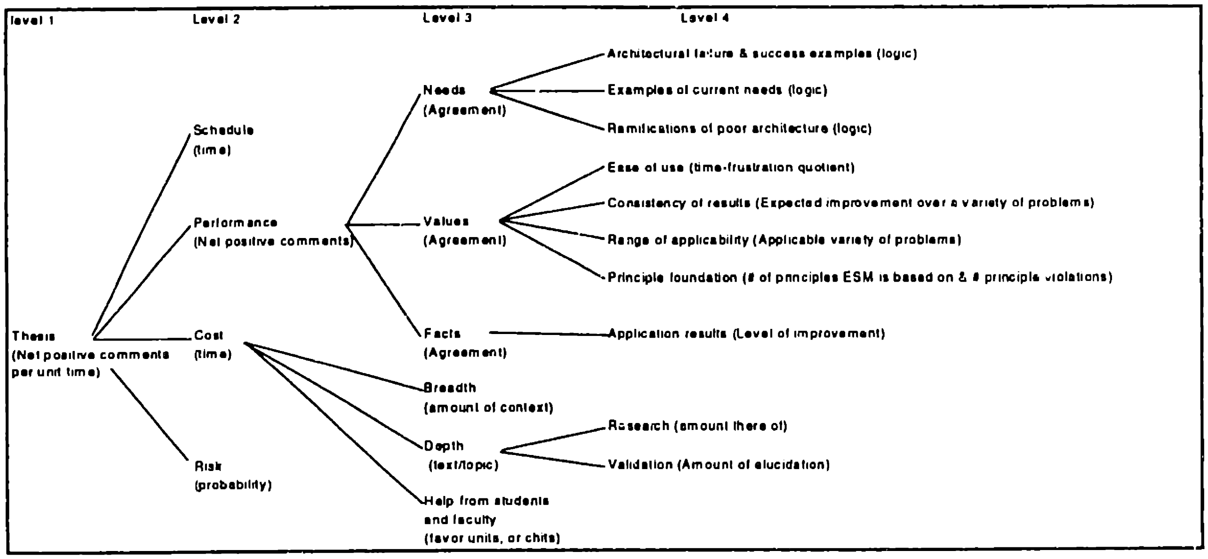


Figure 35. Metric decomposition for thesis design

Needs refers to the value in what one is trying to accomplish. The creation of 'white elephants[8]' is the result of a poorly understood need. Historical examples, current needs, and the ramifications of good and bad system architecture were presented in the introduction to establish need. The descriptions of need were based on logic so this was chosen as the "unit" for each need subelement.

Values refer to what people are looking for. The ESM method will benefit the user if it possesses the characteristics shown in Figure 35. These four value elements were based on nearly two years of listening to SDM students' critiques of numerous engineering, system architecture, project management, and other methods.

A time-frustration quotient was a way to measure ease of use. The more complicated the more time required to use the method. Complication does not necessarily mean high frustration. A string of tedious tasks can be complex. Frustration refers to the level of abstraction required. A very cookbook method would required little abstraction and have low frustration. High levels of abstract thought at every step could be very frustrating.

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[8] A white elephant is a magnificent creation that has no useful purpose, thus making it nothing more than an intellectual curiosity.

Consistency of results meant you had to expect some architectural improvement over a variety of problems. If results were inconsistent you might not want to use the method very often. Range of applicability is the variety of problems over which you want to be consistent. The larger the foundation of principles the better. Similarly the number of principles violated is an issue. I set a necessary constraint of no violations.

Facts were needed to substantiate value. A proposed method with clear user advantages is not credible if it does not work. Elegant and improved architecture results would have to be shown.

Breadth was defined as the amount of context provided. For example every demonstrated ESM benefit had some discussion of the meaning of the benefit. Potential omissions associated with not performing a step were discussed. These and other ancillary discussions made up context.

Research was simply the amount needed. Every part of the thesis would need research behind it. Validation was the application of research. It was measured by the amount of elucidation given for every description and example. The more elucidation, theoretically the better the communication, which in some nonlinear fashion would drive depth.

The level 4 elements and breadth in level 3 were under my control. No further decomposition could be made without a concept. Application of step three changed my point of view about the thesis but did not change the core of the metric decomposition. You may have noticed that I said I would be satisfied with positive statements about the ESM method. This realization forced the top level metric up two levels to a personal satisfaction goal as shown in Figure 36. Decomposition from this goal identified adjacent systems that affected time allocation. I could not spend all my time on the thesis and maximize personal satisfaction. Therefore thesis design architecture would have to be subject to more constraints.

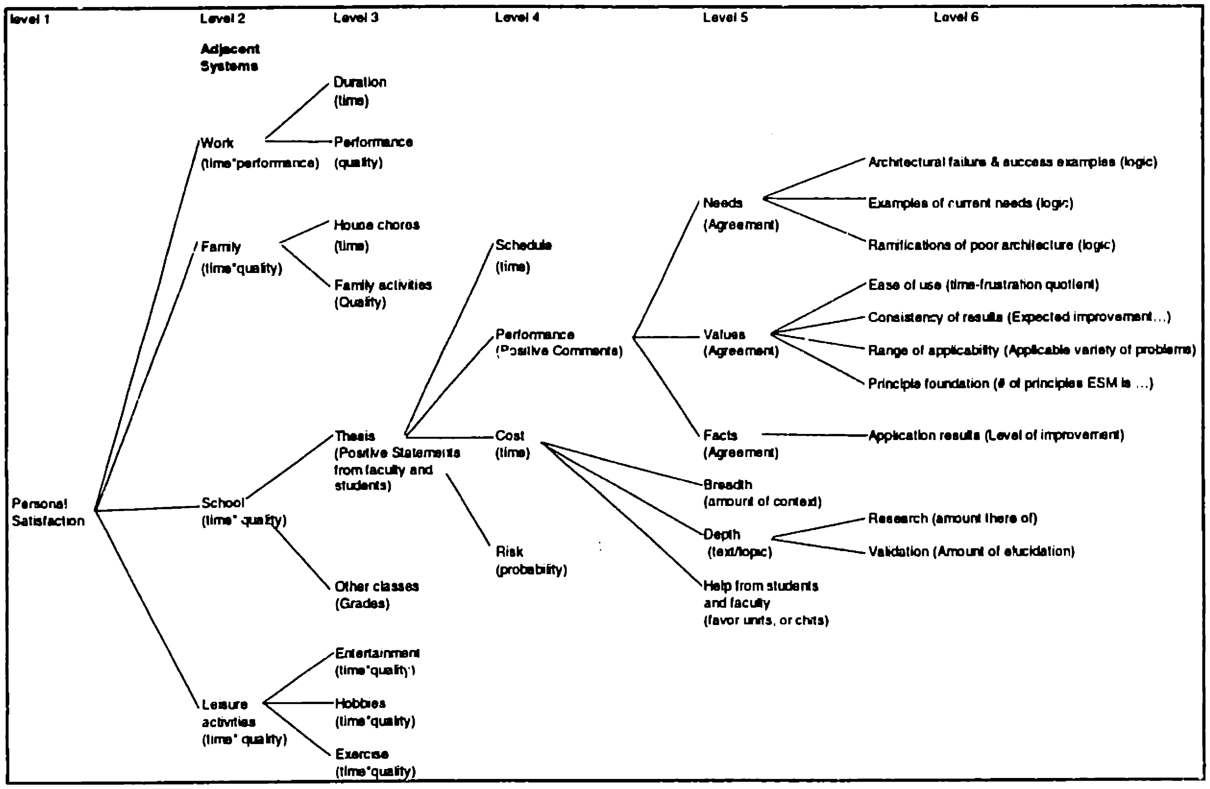

Figure 36. Expanded metric decomposition for thesis design

The DSM for step 4 was applied to the lowest level elements over which I had control (Figure 37). The results showed independent chunks of highly coupled elements. The needs chunk was independent of the other branches. Therefor the chunk was initially removed from the design process because it could be easily inserted later.

	Architectural failures and successes	Current system architecture needs	Ramifications of poor system architecture	Ease of use	Consistency of results	Range of applicability	Principle foundation	Application results	Breadth	Research	Validation
Architectural failures and successes	-										
Current system architecture needs	X	-									
Ramifications of poor system architecture	X	X	-								
Ease of use				-		X	X			X	X
Consistency of results				X	-	X	X	X			
Range of applicability				X	X	-	X	X			
Principle foundation						X	-	X			
Application results				X	X	X	X	-			
Breadth				X	X	X	X	X	-	X	X
Research	X	X	X	X	X	X	X	X	X	-	X
Validation				X	X	X	X	X	X	X	-

Figure 37. DSM for thesis design

The values and facts chunk was very highly coupled. For example to assess ease of use the range of applicability and flexibility of principle application need to be known.
By applying similar logic to the rest of the needs and facts element intersections you see why the chunk is almost fully coupled.

Breadth, research and validation are mutual functions of the needs and facts branches. Likewise breadth, research and validation are mutual functions of each other. Note that ease of use is also a function of research and validation, which constitute depth. Depth has a loose correlation to document length. I considered learning ESM to be part of ease of use. If the thesis were too long ESM would be perceived as too difficult to learn.

Constraints were noted and kept as a reference. After inspecting the metric decomposition I felt that the top level goal was most sensitive to all of the values and the facts elements together as a group. Realistically speaking cost was fixed at about 50% of my available study time at home and 25% my available time at school.

Architecture conceptualization focused on the high coupling within between values and facts branches. It implied that a common integrated chunk would be required. The only satisfactory concept was to have a highly example based thesis. By careful example selection I would be able to show all of the needs and facts elements.

A block diagram of the thesis organization and how it feeds into the higher level elements is shown in Figure 38. The thesis is comprised of the knobs (lowest level elements) I could turn. The block of examples provides values and facts. The DSM results showed research to be integral to all elements. Research really drove the quality of the facts and values elements so it is shown feeding into the thesis. Validation is a fall out from the number of examples. Validation combined with research provided thesis depth. Breadth in the form of context is integral with each example so it is part of the chunk. Breadth is also provided by the diversity of examples selected.

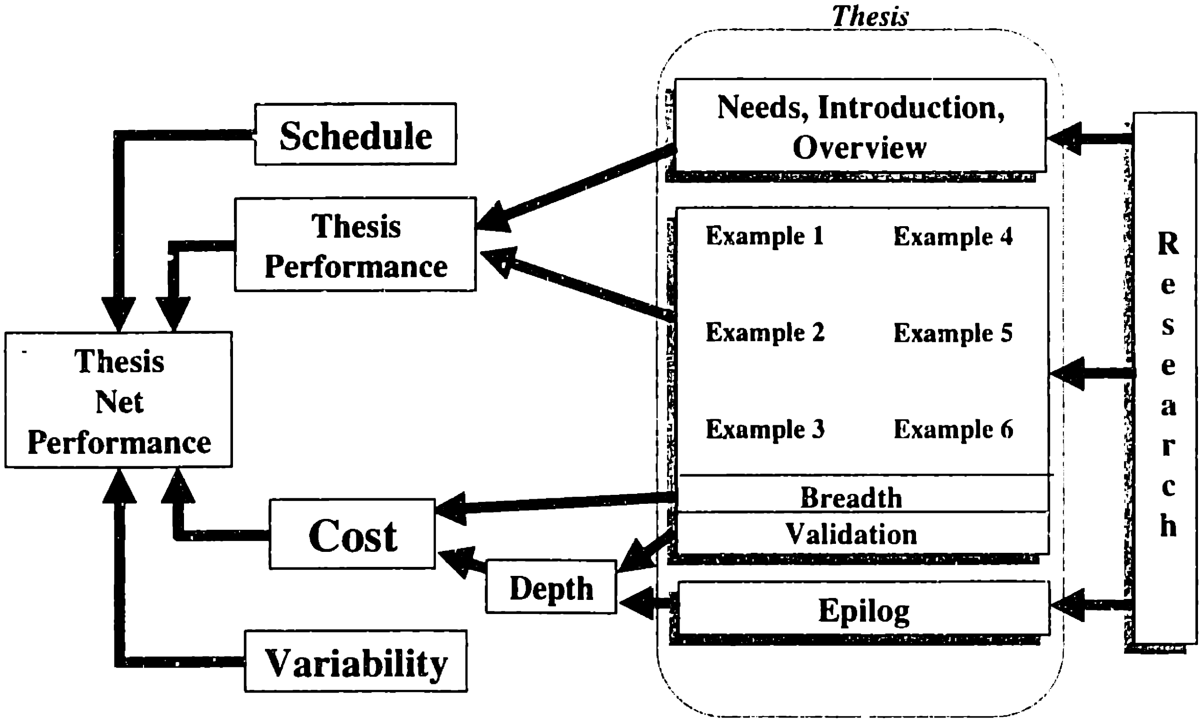

Figure 38. Block diagram of thesis organization

Needs, introduction, and ESM method overview are lumped together at the top. Each independently adds to thesis performance. Any creation comes about through a process. The thesis is the resulting form. An epilog was added to provide useful process information related to the thesis. The epilog characterizes the depth of the research.

Schedule, thesis performance, and cost were explained earlier. Variability is risk in hindsight. At the beginning of a project risk is the amount of variability you might experience.

Other thesis formats (forms) were explored but none satisfied the requirements (functions) identified by the DSM as well. Cleaving the performance section by needs, values, and facts or even by individual elements became very cumbersome because references constantly had to be made to other elements. Examples allow the reader to see functional connections and iterations in context (with breadth) which greatly aids understanding.

Performance, cost, and schedule met or exceeded respective requirements and constraints. Variability was as expected. All the fits and starts were nominal. This leaves thesis performance as the remaining result. To date all peer and faculty reviews have been favorable. In fact fundamental ESM findings are now integrated into the System Architecture course conducted at MIT as part of the System Design and Management Program. My faith in finding a useful system architectural method appears to have succeeded.

Recommendations for Further Research

The new product architecture example shows why complexity is a key parameter. Many design variables are a function of complexity. Quantification of complexity is an elusive task. If a method could be developed it would work well within ESM metric decomposition.

A set of experiments comparing ESM to other architectural methods would be a good way to quantify its benefits. For a given set of homework assignments I would like to see half of a class use ESM and the other half use some other approach. Comparison of results with some kind of numerical scoring could be used to quantify results. Student feedback could be used to improve various aspects as well.

Epilog, The ESM Development Process

The story behind any creative work can be as valuable as the work itself. For this reason I have described the process by which I arrived at the ESM method. There were many early fits and starts in the process. Development of ESM took me down more dead ends than I care to remember. Maybe this account will save someone time in the future or spark a fresh thought that may lead to an improved related work.

Through out the SDM program we had been exposed to a number of system architecture and system engineering methods. My first attempts at organizing upstream influences were based on existing methods. Direct or modified applications of axiomatic design, form and function, QFD, DSM, and others did not work. After a lot of consternation I realized that all of these methods required a concept in order to work. I knew that the upstream influences drove the concept so I reasoned that something was needed in front of these methods. I attempted to integrate new front ends but none of them worked well. The necessity of a concept for each method still upset the neutrality of the upstream elements. I began to look at the equivalent form and function side of each method. The form side was impossible to decompose without a concept. However, by judicious selection of decomposition elements I found functional decomposition could be done solution neutral a level or two before a concept was required. I then began to work backwards away from the concept looking at each higher super system. I found that I could go up several levels or more along this chain and still identify influential elements. When I reached a super system element metric that would not be affected by concept selection I backed down one level and began to do a full decomposition tree towards the concept. In general three to seven levels could be reached in solution neutral space before a concept had to be selected. I noticed there was a clean division between the metric decomposition and where concept selection was required. The decomposition was not only solution neutral, it was also architectural method neutral. All of the elements identified in the decomposition could be mapped into most of the system architecture and system engineering methods. At this point no further effort was put into existing concept specific methods.

The importance of the top level goal became evident since everything cascaded from there. The goal set was then established as step 1. I expended a lot of time doing solution neutral decompositions. As an experiment I began to use heuristics and principles as criteria for decomposing elements. I found this approach to work very well. I also experimented with quantified numerical connections among elements. This is straight forward to do as long as the goal is numerical. Since most engineering problems are numerical and evaluated by a metric the solution neutral decomposition was renamed metric decomposition. Experimentation with "units" on nonnumerical problems showed the same "accounting" benefits. As with physical quantities, nouns used as nonnumerical elements need clear definitions.

As I worked through examples I found myself constantly checking the upper and lower boundaries of the metric decomposition. Many times corrections were needed. So this was made into a discrete step.

Once all the lowest level elements were identified it was clear that many were functions of each other. Sometimes they were the duplicated. By inspection you could also tell some were more important than others. The DSM is a natural when it comes to identifying functional and iterative relationships so its application was chosen as the next step.

Adjacent systems are always present so it was natural to perform the DSM step again to see if adjacent system elements needed to be in the system. The remaining two steps, constraints identification, sensitivity analysis are familiar system engineering tasks. Architectural evaluation is really a place holder for 'architect, do your thing'. As stated before, no method gives you the solution, it only helps you frame it, you have to come up with the ideas and test them out.

All of the steps were identified by late summer of 1998. From that time to the end of 1998 I continuously tested the method on a number of problems. Each time it seemed to work. I was able to understand problems with more clarity and conceive of better solutions. Along the way I found a number of beneficial nuances of ESM. The examples were selected to highlight these as well as show the broad applicability of ESM.

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