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THREE DESIGN TOOL FOCUSED CASE STUDIES OF MECHANICAL ENGINEERING DESIGN PROJECTS

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THREE DESIGN TOOL FOCUSED CASE STUDIES OF MECHANICAL ENGINEERING DESIGN PROJECTS

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Mechanical Engineering

by
William Stuart Miller
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Accepted by:
Joshua D. Summers, Committee Chair
Gregory M. Mocko
Michael L. Mears

ABSTRACT

Three long term mechanical engineering design projects spanning 24 months, 12 months, and 4 months are examined in this thesis. These projects are used to explore the development of a way to represent information flow throughout the design process with respect to design tools used. This is a first step in a broader effort to formalize 1) modeling of design processes, 2) establishing case study research as a formal approach to design research, and 3) developing new design process tools.

A survey of existing models compares the differences between current approaches and the limitations of each. Inspired by IDEF0, an altered process model is presented in an attempt to increase the information captured by the designer when using and constructing the process models. The name of the model is Design Enabler Information Maps (DEIM) and its requirements needed for construction are discussed in the context of the three case projects.

By developing a DEIM representation for each project, this thesis explores the benefit of this approach. In constructing a DEIM of a project, design activities with no productive merit, or design process dead-ends are identified. Information that is critical to design process completion is also identified in the context of its application. Furthermore, the need of a formal tool to represent complex design processes is established. The observations drawn from this thesis lay a foundation enabling future designers to better understand, represent, modify, and complete design processes by using case studies in design research.

DEDICATION

This work is dedicated to my love, Jessica, my parents, Rick and Joy, and my sister, JoAnna. Their enduring love, patience, encouragement, and sacrifices have allowed me to immerse myself in work that I absolutely love doing. They have tolerated many seemingly random and obscure discussions about diverse topics throughout the years which have shaped me into a researcher capable of completing this thesis. It is through these fine people that this work was accomplished. I thank them for always supporting, affirming, and being there for me. Through their love, they have allowed me to achieve things that I could only dream of. To each of them I give my deepest and most sincere appreciation for enabling me to live the life that I have experienced and do the things that I have done. They all are truly wonderful and mean the world to me.

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I am grateful to Dr. Mocko for spurring many intellectual discussions and being available for advice in the past couple of years. His time, experience, and patience while I was growing into an engineer, is much appreciated. I thank him much for that.

I am also grateful to Dr. Mears. Whether in research projects or classroom discussions, he has been a friend as well as a wise colleague. I thank him for his time, wisdom, and willingness to let me learn.

I thank the generosity of my sponsors for funding my research. Environmental America Inc., Wright Metal Products Inc., and Michelin Tire Co. have each contributed greatly to developing my abilities as a designer and they all are much appreciated.

I thank all the members of the AiD, EIM, and CREDO labs. They all have been great to work with and have contributed to my success, through intellectual and sometimes not so intellectual discussions and side by side work. To Ajit, Ben, Chiradeep, David, Jonathan, Pavan, Santosh, Sudhakar, Srinivasan and everyone else, I thank you and wish you the very best in all that you may do.

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Chapter 1

MOTIVATION

1.1. Engineers and Design

Engineers exploit an understanding of scientific phenomena while applying lessons learned from past experiences when executing design projects. Designers reach solutions which benefit the customer safely and completely by applying physical laws that govern the behavior of real world entities. Thus, the word "design" can refer to several different meanings (Otto & Wood, 2001; Ulrich & Eppinger, 2008). Design can be a process of events or an artifact such as a physical object (Ullman, 1997; Pahl & Beitz, 1995; Hazelrigg, 1998). Design can also be related to a method by which ideas and things are created (Asimov, 1962; Simon H. A., 1996). Design can refer to many different things and can be both a noun and a verb (Pahl & Beitz, 1995; Simon H. A., 1996; Ullman, 1997). For this research, the design process is of interest. Therefore, from this point on, design process shall be the context in which things are discussed, unless noted differently.

The design process is a flexible, high level, logical network of activities to be performed and/or design tools to be used for the entire act of designing an artifact, formed by choosing desirable candidate(s) from a set of viable activities/design tools based on certain objectives (Hazelrigg, 1998). The design process is the collaboration of scientific "know how" with mental and physical steps being taken toward the goal of arriving at a satisfying solution (Simon, Kotovsky, & Cagan, 2001). It is a social activity which allows the generation of physical and intellectual property from mental organization and physical tasks (Leifer & Tang, 1988). Engineers perform design processes often with varying degrees of success. The goal of this thesis is to enhance the ability of designers to understand and therefore complete design processes.

1.2. Design Process Measures

The design community has several measures of design success (Yang, 2007). One of these, product function, relates to how well the design solution accomplishes the tasks it has been given (Pahl & Beitz, 1995). An example of this could be vehicle cornering performance. When designing cars, automobile manufacturers specifically require certain performance levels to be achievable by the car. If the manufacturers of a car desire it to have a cornering acceleration of 0.9 G's then the actual cars can be tested to see how well they function. When tested, the car will exceed the cornering requirement, meet the requirement, or fall short of the required cornering acceleration. This result can lead to conclusions about the process which produced the car. If desirable results are found, then the design process can be considered successful. However, if the performance of the car is lower than the desired value, some conclude that the process which produced the car must have been unsuccessful, thereby causing the lack of performance.

Another common metric is customer opinion, a subjective measure. This metric can vary with aesthetics, comfort, appeal, or market trends (Kirschman, Fadel, & Jara-Almonte, 1996). A way to measure customer opinion of the design process could be to record the sales to consumers, or the market shares sold for a specific product. A better design process would yield better products selling more units than the competitor.

Another more quantified success metric is efficiency (Atkinson, 1999). This measure is used to find the time and cost to design. This could be measured as the time the designers take in the design process to develop the final product. It is recognized that many different methods of success evaluation in design exist (Ulrich & Eppinger, 2008). This thesis is intended to enable these metrics for use in evaluating design processes. The individual details of each success metric are not needed. Rather, the selection of success measures will be left to the researcher using the work presented in this thesis on their own research. It is sufficient to know that many diverse options exist which can measure a design process' success.

Discrepancies exist in the academic community about which success measures are valid (Sobek II, 2007). Only a handful of success metrics for design processes exist, some of which are shown below in Table 1.1. In the table, the various success metrics are shown along the left side. Each has a definition as well as the critical information required to measure the success of the process in that manner. The person responsible for this process success evaluation is also noted.

Table 1.1: Design Process Success Measures

Success Metric	Definition	Information Required	Personnel Required	Relative / Absolute	Direct / Indirect	Internal / External	Qualitative / Quantitative	Ad Hoc / Post Hoc	Reference
Client Satisfaction	The design has approval of client	Client Opinion	Client	A	I	E	Qual	P	Yang
Design Quality	The design has sufficient product characteristics	Test Results	Test Performer	R	I	E	Quan	P	Yang
Requirement Satisfaction	The design has met all of the requirements	Requirements List	Designer	A	I	I	Qual	P	Yang
Design Feasibility	The design performs logically without waste	Function Means	Designer	R	I	E	Qual	P	Sobek II
Design Creativity	The design consists of novel solutions	Current Examples	Designer	R	I	E	Qual	P	Yang
Design Simplicity	The design performs with minimal components	Components	Designer	R	I	E	Qual	P	Sobek II
Design Punctuality	The process was completed within the given timeframe	Time Requirements	Designer	A	D	E	Quan	A	Yang
Designer Satisfaction	The designers have approved the product	Designer Opinion	Designer	A	I	E	Qual	A	Yang
Design Sales	The design sells a sufficient number of units	Sales Report	Salesman	A	I	E	Quan	P	Yang

The fifth column states if the metric is a relative or absolute measure, representing the ability for the measure to be perceived differently by various users. An absolute metric will yield the same result for all readers while a relative metric will yield results which vary from reader to reader. The sixth column states if the success metric is a direct or indirect measure of the design process. A direct metric will yield success measures from the process. An indirect measure will measure success from a product produced by the design process. The internal or external column refers to the perspective of analysis being performed on the process. Internal metrics will analyze the success from an entity within the design process such as a specific document or stage. External metrics will analyze the product of the design process or some characteristic thereof. The qualitative vs. quantitative column refers to the type of measure that is given. A qualitative metric will give descriptive measures about the processes success. A quantitative metric will give numerical rating of the process relative to some standard unit. Finally, the ad hoc vs. post hoc column states the time in which the success metric can evaluate the process. Ad hoc metrics can determine the success of the single design process as it is being performed. Post hoc metrics must wait evaluate the process “after the fact”.

Each success metric listed can be used by a variety of users. Designers, managers, and researchers all use success metrics of processes. Naturally, each user has their preferred success metric which caters best to their particular area of interest. However, each category of the metrics can be evaluated independently and used to highlight the most desirable traits within the options given. An absolute metric would be beneficial over a relative metric because any ambiguity about the results would be eliminated. A direct measure of the design process is desirable because directly measuring the process leaves less room for interpretation errors that are present when the products are evaluated. An internal success metric is desired because it gives results from specific components of the design process. An external metric can only evaluate the process as a whole. A quantitative metric would allow relative comparison of multiple processes while a qualitative metric could only say that the process was good or bad. Finally, an ad hoc measure would be more beneficial than a post hoc measure because the evaluation can occur in real time, thus allowing controlling actions to be taken. It can be seen that an "ideal" metric cannot be identified.

None of the known success metrics are universally accepted as the single best option because the users each emphasize success metrics that pertain to their own area of interest, and are concerned less about the others. Hence, determining success of a design process is a problem. Engineers should be able to compare the success of different design processes evaluated by different researchers with dependable accuracy about the relationships between the two success metrics used. A solution to this problem is needed. This thesis provides the first step towards this goal, modeling the design process with respect to information flowing throughout it, thereby allowing designers to better understand the design process and evaluate it.

1.3. Analysis of Design Processes

For design processes to be comparatively evaluated through different metrics, the processes and their goals must be clearly defined and then related to each other. To fully explain the process, it should be broken down into sections or stages which can give more detailed understanding of the change of information throughout the process. Doing so not only gives designers understanding of what the process accomplishes, but also how it accomplishes it. Then each stage can be further analyzed to determine the individual steps taken within that stage to achieve that stage's deliverables and how those interact with subsequent stages. Each step within the design stage will have a more refined goal which is closer to what the design process is to achieve. Each of these steps can be evaluated to determine the information that enters from the previous step and the information that exits to the next step. The tools used within the design step can be identified as well as their fundamental function. This theory proposed benefit for related research but is considered out of the scope of this thesis.

This hierarchy of the design process is illustrated below in Figure 1.1. Notice how information flows throughout the components of the process. Design steps can occur in loops, repeating and converging on information vital to success. Each design tool or method receives information from other sources, and transmits its exiting information outward to another step. Steps can possess singular and multiple information units which can enter and exit specific process steps. The information produced by any design step should be greater than the sum of its components. The same can be said regarding the design process and its subordinate stages.

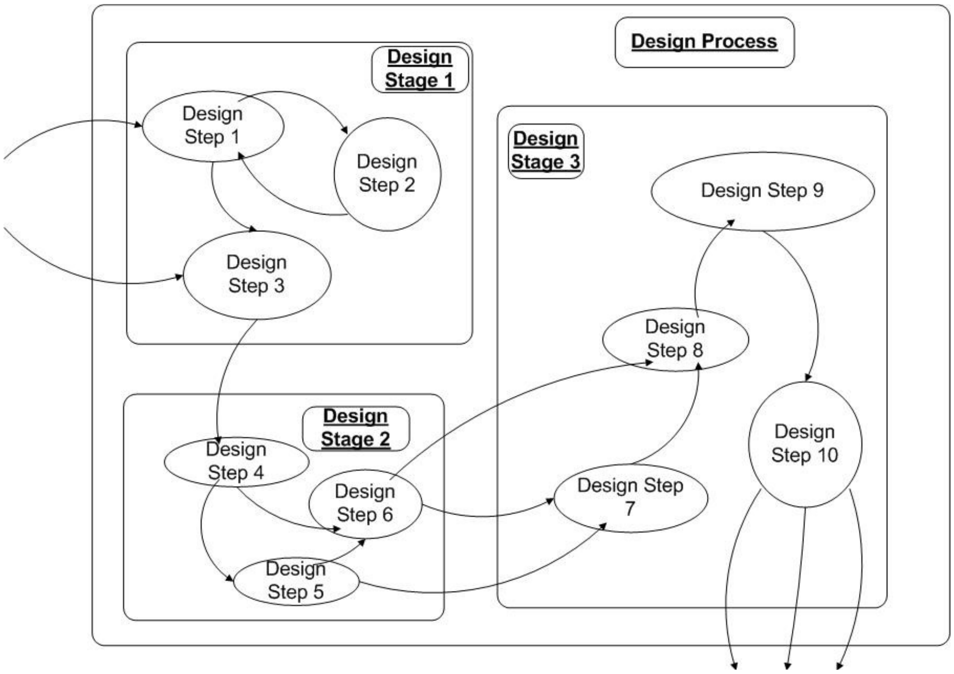


Figure 1.1: Design Process Hierarchy

Progressing through the design process with attention to detail should generate a deep and thorough understanding of the process and gives perspective to how the process achieves its goals. When the proper perspective of the process is attained, analysis steps can be taken to ensure each and all of the goals are met as well as defined properly.

In order to quantify how well a design process has been executed, the process itself must be analyzed (Lockledge & Salustri, 2001). Analyzing processes can be done with various levels of detail resolution. A low detail resolution of the process allows the researcher to retain focus on the overall process goals. It does not lend detailed insight to information interactions within the process. Figure 1.2 shows a low resolution approach to process analysis. This type of analysis builds on the establishment of what is entering and exiting a specific boundary to the process. The result is a coarse representation of the process.

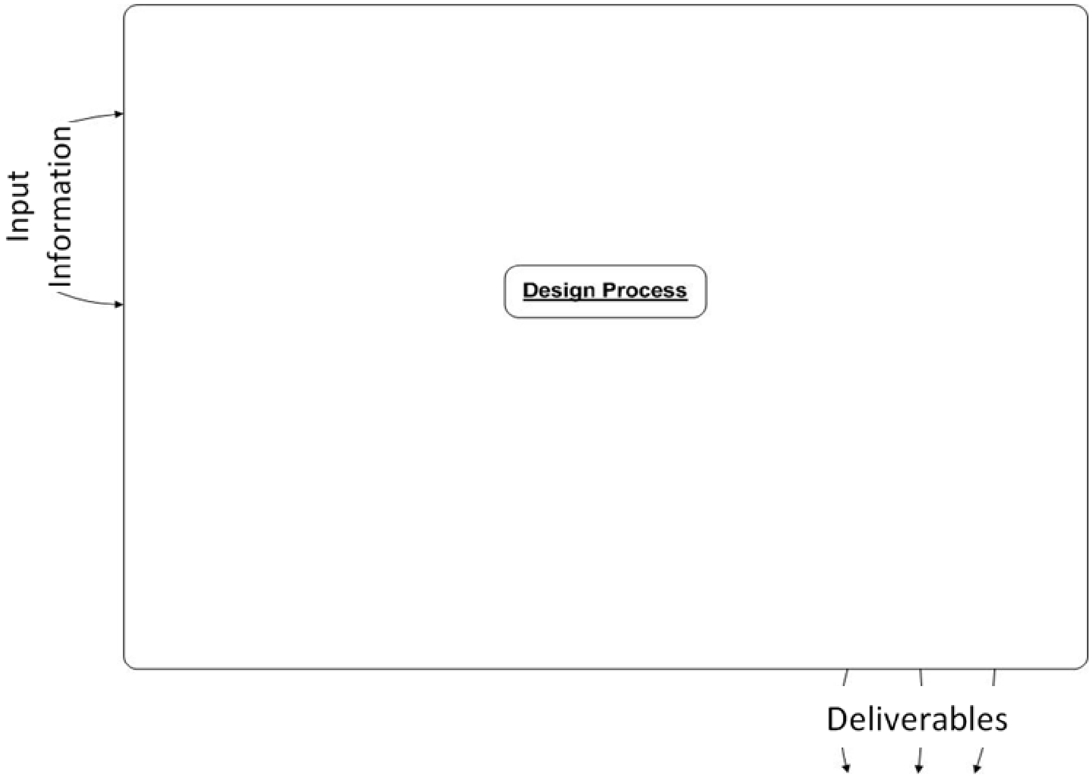


Figure 1.2: Low Detail Resolution

Conversely, in Figure 1.3, a higher detail resolution analysis of processes consuming more time and effort in detailing each step is shown. The work becomes tedious and can go into increasingly deeper detail, which may or may not be needed. This intermediate resolution of detail shows how increasing detail requires increasing effort as well, because the entities being considered increases, thus increasing the work required to analyze.

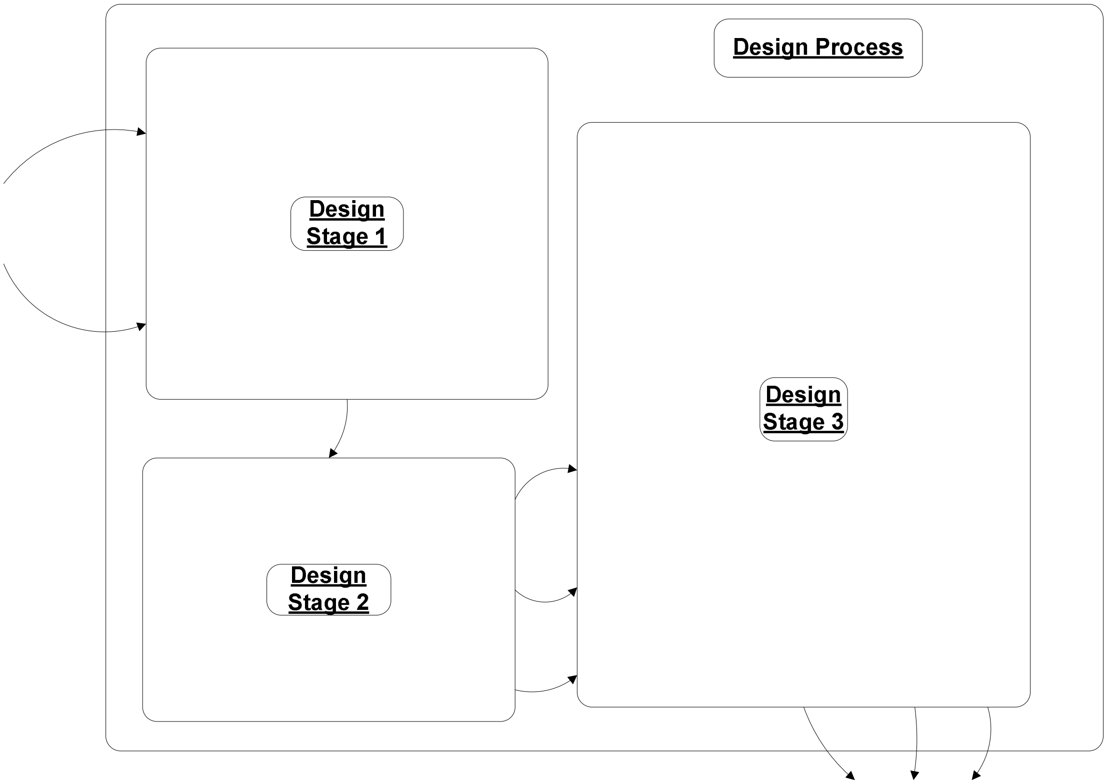


Figure 1.3: Intermediate Detail Resolution

This type of analysis permits the researcher to identify information interactions within the process, therefore identifying additional information within the process that was initially overlooked. Care must be taken to maintain the proper level of detail when analyzing the processes to avoid excessive work when not needed but also to ensure that sufficient detail is considered. A high detailed resolution analysis of the design process is shown in Figure 1.4 which is an extension of the hierarchy defined above. This analysis of the process is considerably more “Step by Step” than a low detail resolution analysis can give. High detail resolution analysis shows that the product of a process is more than a sum of the collected parts (Lockledge & Salustri, 2001). The level of detail being considered for any design process analysis is chosen by the researcher. It is the designer, or as previously discussed, manager or researcher who must be capable of specifying appropriate detail to consider in the evaluation that will not consume enormous processing power yet still yield a sufficient analysis.

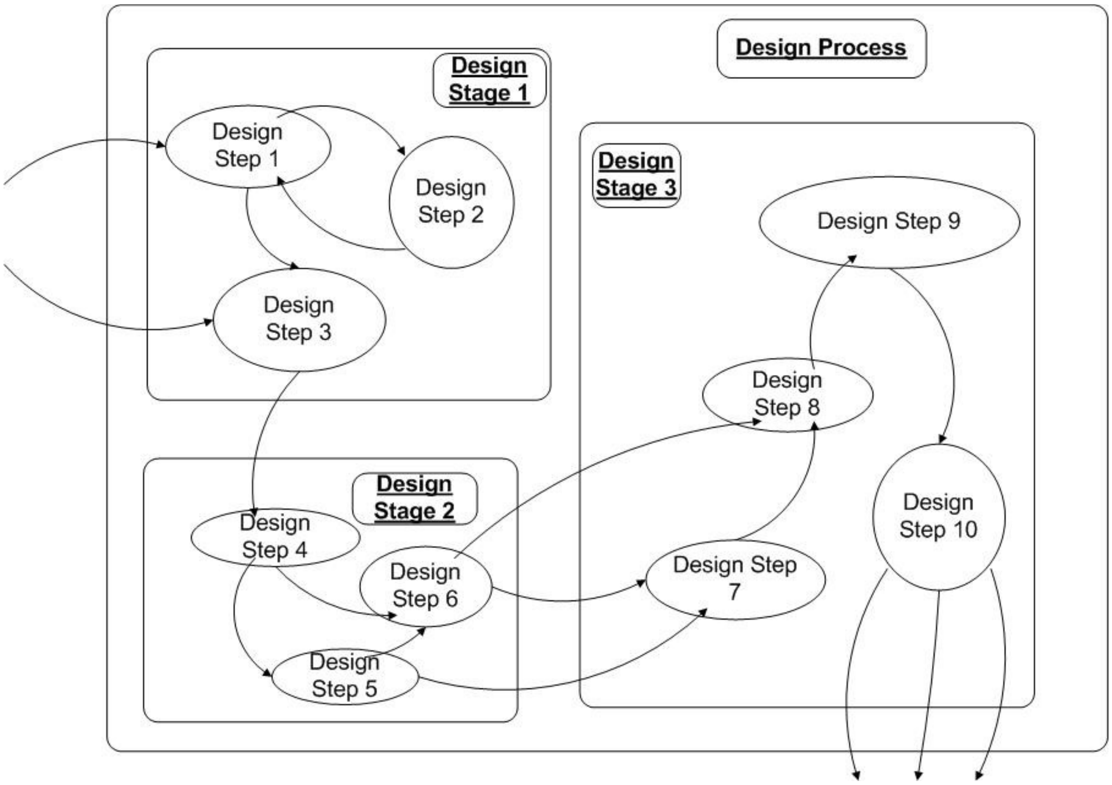


Figure 1.4: High Detail Resolution

Design tools can exist in two different forms; product support and process support. This thesis is concerned with exploring process evaluation design tools to model the use of product support design tools. Product support tools are used within the design process to complete and achieve the design solution. Some examples of these are Function Structures, CAD packages, and Decision Matrices (Ulrich & Eppinger, 2008). Process evaluation tools are used to evaluate and observe the design process itself, thus giving some measure of goodness. These tools may or may not be used to arrive at a solution, but they are frequently used to manage and monitor the design process either en route or after a solution has been achieved.

Analysis of design can be accomplished with several existing tools, albeit with limitations. Program Evaluation and Review Technique (PERT) is an external design tool which is used in scheduling and planning processes (Battista, Pietrosanti, Tamassia, & Tollis, 1989). An illustration of a PERT diagram is below in Figure 1.5. PERT uses vertices to signify events within a process and lines or edges to signify a process. The distance between the vertices or length of the line represents the duration of the specified task. In the figure shown, A is an event which precedes B, and the time duration from A to B can range from 1 to 5 time units. In addition, A also precedes C, with time duration from 3 to 10 time units. However, B precedes C and therefore must be completed before C can begin. Process and event connectivity along with interdependency can be illustrated with PERT diagrams. Supplying dense detail in PERT requires the use of extensive text and can clutter the diagram. PERT is best used to evaluate singular project management entities, such as time.

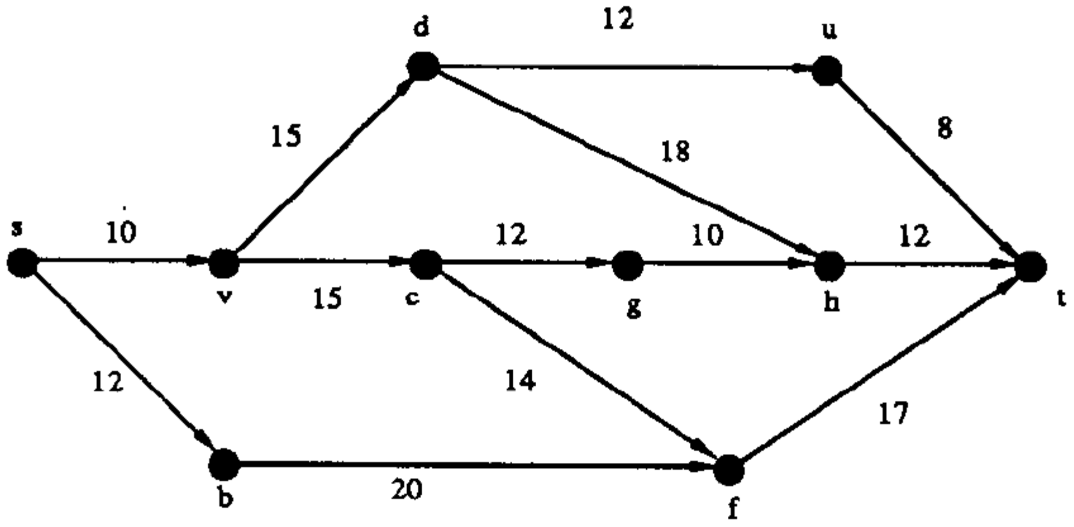


Figure 1.5: PERT Diagram (Battista, Pietrosanti, Tamassia, & Tollis, 1989)

Gantt Charts are another project or process management tool. They are used to present time related information of processes in relevant timeline domains (Maylor, 2001). They are capable of showing schedule expectations, event milestones, and current progress. Much like PERT diagrams, Gantt charts have difficulty in showing multiple information entities on a single diagram without the use of additional text. This tool tends to over simplify planning and leads the user to micromanage processes (Maylor, 2001). Gantt charts cannot discuss reasoning or details about specific events and can show a limited type of entities due to the nature of its display style. A sample Gantt chart is shown below in Figure 1.6. In the figure, Business Maps, Ontological Tactics, Metrics, and Semantic Distance are tasks which take place over periods of time. Specific parties are given responsibility along the vertical axis, and event milestones are shown in specific projects along the horizontal axis according to the time in which they occur.

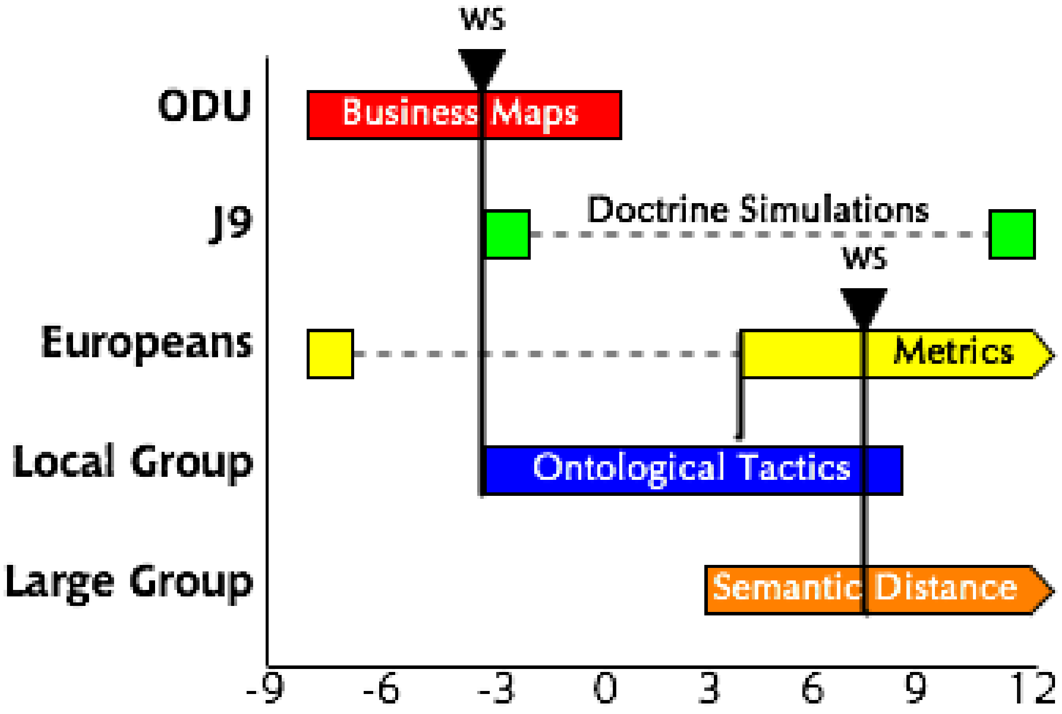


Figure 1.6: Gantt chart (Goranson, 2004)

The ability of the user to modify the evaluation tool for their specific needs does exist, but is often tedious due to evaluation tool restrictions of formatting and application. A process evaluation and analysis tool is needed to allow the users to track the critical information that is important to their individual research. The ability to decompose processes and evaluate each sub-system should prove beneficial for designers, by increasing their understanding of the design process.

Such a tool should facilitate information tracking and evaluation for each step within the process and should display the information produced by performing the specified tasks within that process. If units of information, such as design documents, are generated by a design task, they must either be useful or considered waste. Wasteful information means that the information is not useful in producing a solution and should not be created. If information is created and used later on, but not part of the original intention of that step, the requirements should be revised to include the newly discovered information. This analysis should enable researchers to better understand design processes. Researchers can analyze design projects to use the information available to learn about the process while using the process to learn about the applied case as well.

1.4. Case Studies in Design

One of the most significant tools for design process analysis is case studies (Yin, 2003). Remarkably, case studies are often misunderstood when used as a design process analysis tool (Ahmed, 2007). Case studies are the empirical extraction of data from real world events that are used to view relationships and examine results about design (Teegavarapu & Summers, 2008). They provide relative, fact-based results to qualitative questions (Eisenhardt, 1989). Case studies focus on real world practices to develop theories and methodologies (Teegavarapu & Summers, 2008). They provide a wealth of information about the case that is being studied, but care must be taken in extracting and extrapolating conclusions about the results found (Yin, 2003). It is inappropriate to assume generalizations about variables from case study results without proper construction of the case experiment. Case studies are meant to generalize results for similar cases, without experimental control (Teegavarapu & Summers, 2008). They generate straightforward data from results which apply to a group of design variables, but cannot lend themselves to distinguish the effects of each variable individually.

Yin integrated the use of case studies into research theory by sectioning the issue into designing case studies and case study methods (Yin, 2003). By doing so he allows the engineer or researcher to consciously dissect the topic of case studies so that they can understand how to construct them and how to interpret the results. Eisenhardt applied case studies to theory development by instructing both how to design a case study and how to position the information gained relative to the theory being studied (Eisenhardt, 1989). Hernandez et al. used case studies to validate their design research work by developing the research theory and applying in case studies to discover the results (Hernandez, et al., 2001). The steps of the case study served as the guidelines to generating their required product. Agogino and Hsi used case studies to support exploratory learning in engineering design (Agogino & Hsi, 1993). In their work, the case studies were developed for each of the design variables they were considering. As each case study was executed, a different perspective on the problem was given. The problem could then be addressed and conclusions reached with confidence in the accuracy of the observations.

As can be expected, using case studies often presents challenges to the researcher. The most obvious one is validating the results from the study within the academic community (Eisenhardt, 1989). Years of improper applications of case studies has tainted the use of this tool (Yin, 2003). Thus, academia tends to shun its use, considering it a reckless endeavor. While designing a case study can be difficult, collecting data from case studies can even more laborious. Collecting data can take place in a variety of manners, but tradeoffs of collection cost, collection effort, collection time, and influence on the results exist (Yin, 2003). The researcher must select what information is needed as well as how to extract it and do so without skewing the data. Yin calls this part of "Case Study Design" which Teegavarapu discusses as the five components of utilizing case studies in design research (Teegavarapu & Summers, 2008). The five components represent the high level stages which must be accomplished in case study use. They are:

- Define the case being studied
- State the proposed hypothesis about the case
- Define the unit of analysis for the case
- Relate the data to the propositions
- Interpret the case study results

These steps are illustrated below in Figure 1.7 (Teegavarapu & Summers, 2008). Using case studies starts with identifying the problem of interest. This step is organizational, yet critical. Without proper definition of the problem, work could veer off track and become unproductive. From the problem definition, a hypothesis is formed. Then this hypothesis is tested via experiments and/or observations concerning the case. The data is then collected and organized so that it can be analyzed. The observations are then compared to the hypothesis, and should discrepancies arise, will initiate more testing via experiments. Once the hypothesis is proved with the data, conclusions can be drawn about the case, and the results communicated to others who may be concerned with the work.

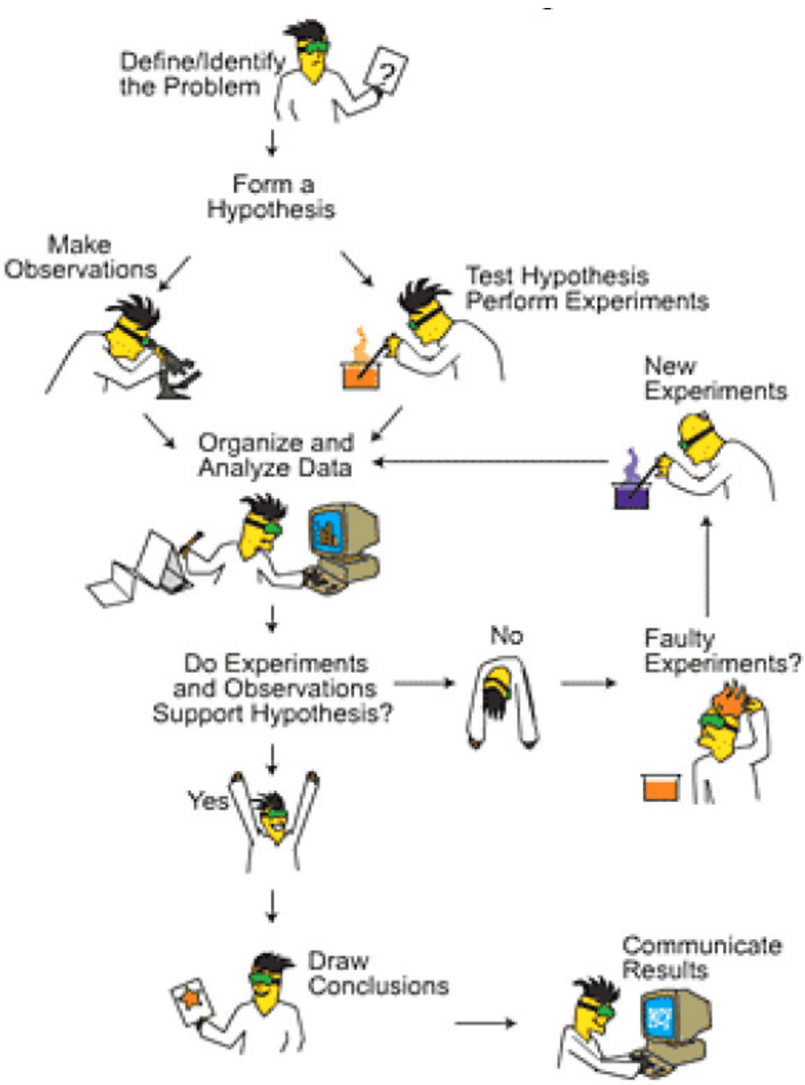


Figure 1.7: Case Study Steps (Teegavarapu & Summers, 2008)

To extrapolate the conclusions to a theoretical application, properly constrained studies must be established (Yin, 2003). Developing such a bank of studies is difficult and resource consuming because the similarity of multiple cases is subjective and not easily compared. Each case studied must be similar to the whole, but contain selected differences as to allow extrapolation of behaviors. Quantifying similarity is not a standard act, thus making the design of the case study vary from researcher to researcher. Finding sufficient cases to study that are properly similar is difficult at best, and occurrences that arise naturally are rare in academia. Case study use in design is a powerful idea, but consists of many aspects which must be carefully considered when developing theories. The ambiguity of case variables must be minimized and the correlation of variables to theory should be fully defined.

Teegavarapu discusses case studies as an empirical research method used to investigate a contemporary phenomenon, focusing on the dynamics of the case, within its real life context (Teegavarapu & Summers, 2008). Using case studies is said to be an all encompassing method which covers the problem definition, hypothesis formation, and collection and analysis of data stages. Case studies enable the designer to answer how and why questions about the specific occurrence. They do not allow the user to control variables, however, which would classify the study as an experiment. A typical case study will consist of three phases which are defined as;

1. Define and Design phase
2. Prepare, Collect, and Analyze phase
3. Analyze and Conclude phase

Common objections exist in case study use. One of these is that generalizations cannot be formed from a single case. Another is that case study research lacks rigor, which is due to the researcher and not the method. Traditionally case studies are executed over long periods of time, but this is believed to be caused by unnecessary and invalid tasks being performed within the study. Finally, it is believed that case studies are biased by nature. Some argue that research methods in general are biased; therefore case studies are not more biased any more than other research method (Teegavarapu & Summers, 2008).

Case studies possess tremendous power in analyzing design processes, but wielding such power requires care. Despite the informational gain potential, case studies are easy to execute incorrectly. This reduces validity of the results as well as the beneficial experience gained by the researcher who executed the case study. To harness the educational value of case studies better, using case studies should become less exhaustive and more "second nature" to the researcher. By decreasing the effort required to use case studies, one can hope that both the benefit from and the use of case studies would increase.

In order to enhance the use of case studies within design, one should be able to visualize the design process, without affecting the products of the process. This would allow the researcher to know how to construct the case study without corrupting the data. The visualization, as well as the results generated from it must be easily observed and understood. The information gained from visualizing the design process should not require exhaustive effort to generate or comprehend thus reducing the probability of erroneous case study design and extrapolation. The identification of multiple similar cases should not require exhaustive efforts but should rather be an observation of the two cases. This would signify an enhanced use of case studies within design research. By improving the use of case studies, engineers can focus more on what can be learned rather than doing tasks correctly. In doing so, effort can more appropriately be given to understanding the process being analyzed.

1.5. Design Process Models

A design process model is needed. Some of the design process models that currently exist are the Collaborative Design Model, Decision Based Model, Systematic Model, Information Model, Generic Model, Change Propagation Model, and Cognitive Model. These are discussed in detail in Chapter Three; however none of these models are globally accepted by the research community (Ullman, 1997; Sim & Duffy, 2003; Pahl & Beitz, 1995). If a design process model existed which could communicate the information that the user needed, universally, understanding and manipulating design would require much less work. A way to communicate requirements of design processes as well as the way information transforms and flows throughout the design process is needed.

Designers have product support design tools at their disposal. Using this as a starting point, a design tool based approach to modeling the design process could prove beneficial. Since design tools cannot compose a design process alone, the information which flows throughout the tools must also be considered. Using this approach, the information that enters and exits design tools could be connected to plot the design process evolution as it progresses.

Representing design processes with both product support and process evaluation tools could lend an advantage over other process models when representing design processes. With a model of design processes showing the importance and function of design tools, researchers could increase their understanding of design processes. Furthermore, the design process can be analyzed in individual portions as well as a whole to reveal fundamental relationships that are hidden within the design process.

1.6. A Needed Representation

The ability to prescribe the level of detail one wishes to study would enable researchers to dissect a design process in a manner which suits their needs best. A visual design tool based representation of design processes would enable researchers to modify the design process, as defined as a network of activities to be performed and/or design tools to be used both in theory and practice, in order to better guide the process to the results. When the design process is completely disassembled, the components and relationships within the process can be studied, thus allowing thorough understanding of the effect of each part of the process. This deep understanding could expose quantitative data about the effect of each design parameter and allow designers the ability to critique the design process. Having this concrete data would reduce the need of expert experience and would allow design process construction to be built on rules and facts which are easily quantified.

Observing and measuring precise rules and facts about design processes has been subjective for decades, but with the ability to "see" design, one could predict performance of designers engaged in design processes (Tufte, 1986). Engineers and designers are typically visually oriented people (Henderson, 1999). However, when design processes are represented, it is traditionally in text form such as reports. It is logical that if design processes could be illustrated with visual images, then the designers and engineers who use them so frequently would be able to better understand and manipulate the process to suit their needs.

Such a visualization of design should be capable of representing many if not any design process model. Researchers should be able to construct such a representation in context with their own domain of information. The readers should be able to locate and follow any specified entity through the entire design process with ease. All of this should be done visually, with text only used for labeling. This model would enable performing visual and content based comparisons of multiple design processes. With such enhancements in design analysis, future researchers can build experiments to control design process outcomes. Such experiments would prove useful for design education as well as research projects. These benefits mean that researchers in design can improve design education as well as design practice through implementing a visual process representation toward a better understanding of how design processes work. Additionally, all of this could be applied to case study research, giving engineers a more powerful tool to advance the understanding of design. By observing the information flowing through each activity within the design process bottlenecks can be spotted and addressed to streamline efficiency.

1.7. Representation Requirements

Fully understanding the design process and what happens within the context of design would allow engineers to improve the design process to suit the resources that are available to the designer. The design process itself could be manipulated intentionally to control the design process and learn about the effects that each component has on the final solution, thus blurring the line between experiments and case studies. Beneficial gains such as these would increase the value and thereby, acceptance of case study research and could possibly place the use of case studies foremost in design engineering.

By creating this new visualization method, the usability of case studies should improve. This is accomplished by using case studies to learn about the process and modify it. With this improved understanding, the process can be used to improve the use of case studies in analyzing design processes. In the future, case studies standardize analyzing the design process. By implementing the aforementioned visualization method, case studies can become commonly used by many researchers and something that can work effectively to guide the construction of experiments as well as design processes for engineers.

Thus, the development of a new process visualization tool is warranted. This thesis is about developing a visual representation scheme to illustrate information within design processes. This visualization method would enable the designer to see information that is of interest throughout the design process. As a result, one can select any performance metric desired to gage the success of a given design process. Additionally, multiple processes can be compared against each other on similar criteria. As the process representation is constructed, the information of interest will develop from the first step of design to the final delivery of the product. Once complete, the process maps will allow researchers to follow critical information through the process as well as plan ahead to ensure that the current design process will yield something of sufficient value to the customer.

This work will model three design projects in which the author was involved. For each of these projects, a visual design process map will be constructed representing the actual information and actions taken within the real life design project to develop a process representation and analysis tool. It is believed that throughout the development of these maps, the ability to represent design processes can be enhanced. Through these projects, the maps will be developed and tested, to show that visualization of design processes is possible and beneficial to researchers.

Chapter 2

EXISTING DESIGN PROCESS MODELS

2.1. Process Model Requirements

Process models are tools which simulate and emulate the behavior, interactions, and reactions of a system. Models of control systems are typically mathematical expressions. Models of physical artifacts can often be CAD models or physical prototypes used for testing. Models of design processes determine the structure and interrelationships of the individual tasks that comprise the process (Smith & Eppinger, 1997). They accomplish this by dividing the problem into appropriate sections which are classified according to the domain of the process. By using process models, designers can dissolve processes into smaller, more manageable tasks which are easier to understand represent (Ostergaard & Summers, 2003). The information gained from each individual task can then be combined to represent a more complete understanding of the entire process (Finger & Dixon, 1989).

However, process models are high level representations of the activities taken in a process. They can yield abstract relationships of process components but require specific context to the problem in order to predict precise future outcomes for the process. Models can represent multiple processes, but require context for each to be applicable. A model is a tool which must be used in order for work to be accomplished. A process model cannot represent a design process without the designer properly constructing the process within the confines of the process scope and thus, has limitations. While this is not a negative characteristic of process models, it does mean that something else is needed for information to be gained. As mentioned before, designer interaction is required. Building a process model directly from the process is the current method of construction. This relies heavily on the precision and accuracy of the researcher. Should parts be omitted or errors be made, they will be included in the model. An effort should be made to bridge the gap between actual process and process model. This bridge will enhance the designer's understanding of the process, thereby improving the quality of the model being produced. Improving the way that processes are represented through applying the proposed model to familiar cases will enable observations made from the representation to be compared with real world events for evaluation.

Illustrated below in Figure 2.1, the interactions of the Process, Model, and Designer are shown. Designers want to modify the process. This is often difficult, so designers must first learn about the process. Learning improves understanding, but is often, not sufficient by itself. Therefore designers learn from process models which further teach by representing the process. Then researchers can modify the design process by utilizing the model as they see fit. Researchers can also refine their process models by learning from the process itself. This in turn improves the model's ability to represent the process as well as the designer's ability to change the process.

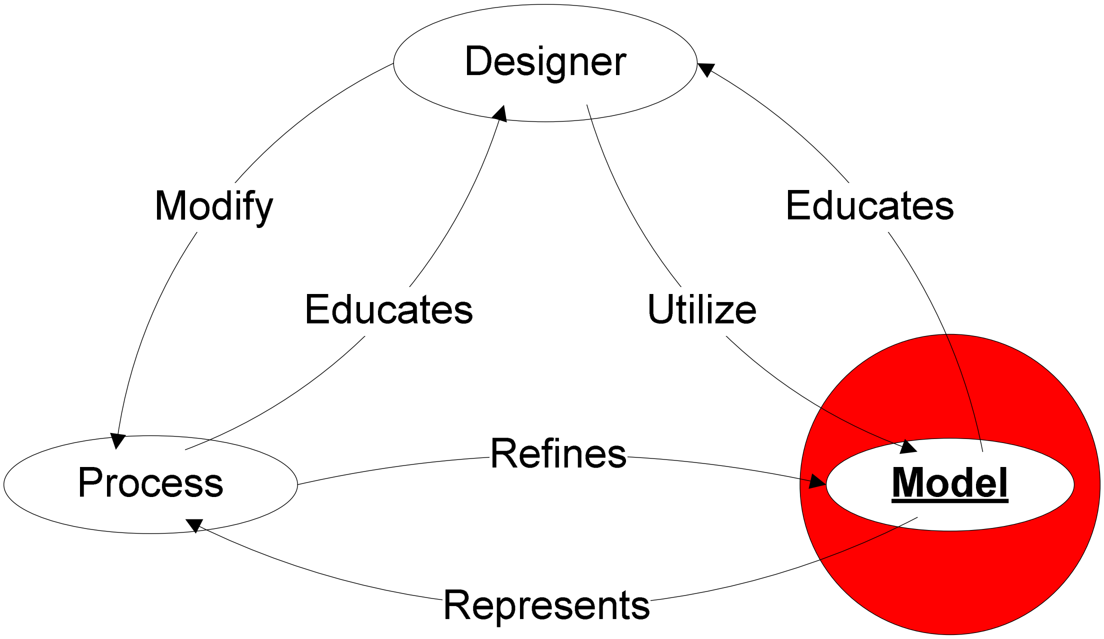


Figure 2.1: Designer Process Model Interactions

Many process models for design exist. Some are listed below in Table 2.1 where the name of the model is followed by a subject column. This column contains the entities that are modeled within the process. Notice how the subjects differ, relating back to the different performance metrics which are used for a variety of reasons. Each of these models is specifically developed for certain use within specified contexts. The third column is the representation style of the model. This is how the information from the model is communicated to the designer. Text representations can be technical reports or notes which describe the model's information. Tabular representations use less text and instead organize the remaining text so that visual reasoning can be used to extract information. Finally, graphic representations are the most open ended and abstract of the representations (Tufte, 1986). These can vary from a photographed image to a graph. The reader is made responsible to capture the information required from the representation. It can be seen that no standard exists to establish proper subject material or representation scheme for process models.

Table 2.1: Design Process Models

Model Name	Subject	Representation	Reference
Collaborative Method	Expertise, Ideas, Resources, Responsibilities	Text, Graphic, Tabular	Ostergaard and Summers
Decision Based Model	Options, Decisions, Selection Processes	Text	Hazelrigg
Systematic Model	Goals, Tasks, Requirements	Text, Graphic	Pahl and Beitz
Information Model	Information, Processes	Text, Graphic	Ullman
Generic Model	Knowledge, Activities	Text, Graphic	Sim and Duffy
DSM	Tasks, Structures, Interrelationships	Tabular	Smith and Eppinger
Change Propagation Model	Components, Sub-systems, Dependencies, Predictions	Text, Graphic, Tabular	Clarkson et al
Cognitive Model	Functions, Skills	Text	Finger and Dixon
Hypertext Model	Features, Functions, Requirements	Text, Graphic, Tabular	Nanard and Nanard
Design Activity Ontology	Information, Activities	Text, Graphic, Tabular	Kumar and Mocko

2.2. The Generic Design Process Model

Sim and Duffy describe the engineering design process as a series of interrelated and connected design activities (A_d) in their generic design process model (Sim & Duffy, 2003). Each activity is aimed at generating some output knowledge (O_k) that the designer can then use to begin the next step until the final solution is reached. For each activity, they state that there must be some design knowledge which serves as input knowledge (I_k). This enters the design activity along with the goals of the activity (G_d) to begin the task. What is produced from the activity is output knowledge which can feed back to refine the design goals as well as the input knowledge until the desired outcome is achieved. The Sim and Duffy model can be seen below in Figure 2.2.

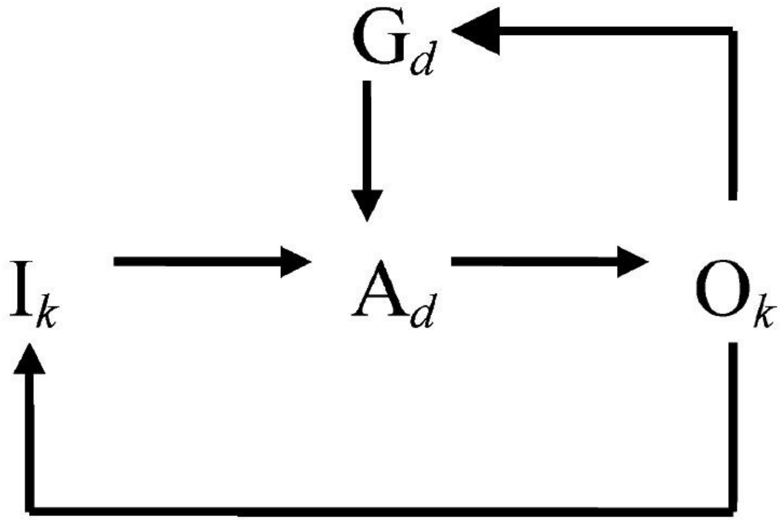


Figure 2.2: Sim and Duffy Design Model (Sim & Duffy, 2003)

By modeling activities, Sim and Duffy consider what they believe to be the most universal and fundamental entity in engineering design, information, which they call knowledge. Tracking information allows designers to relate the model to any specific process with context appropriate to their domain. Following the use of information through design activities enables this model to be applied to many different processes, but still yield better understanding through detailed representation of the information being examined.

Sim and Duffy have formed a list of generic design activities. While the list is fairly exhaustive, classifying a specified information entity can sometimes be tedious. Understanding the context of each category is helpful in properly assigning the activity to the proper classification. The authors primarily use text to represent the model, with the tables and graphs included for support. There exists information in the Sim and Duffy model which may not always be desired by the design researcher. For example, a user may not always want to be concerned with feedback loops, or with design goals. While these are considered valuable to design, the option to include them in a particular study should be at the discretion of the researcher. Refer to (Sim & Duffy, 2003) for more information on the Generic design process model. Additionally, the reader is referred to Kumar and Mocko for extensions of the ontology generated by Sim and Duffy (Kumar & Mocko, 2007). This ontology classifies and organizes information and activities into standardized entities which can be manipulated methodically towards developing a better process understanding. The Sim and Duffy model establishes a good ontology of the atomic element of design and classifies the many forms in which information can exist. This is information that should be built upon and used to enhance design process understanding.

2.3. The TEA Model

Ullman et al. defines the design process as: *the organization and management of people and the information they develop in the evolution of a product* (Ullman, 1997). Building the process on that definition, Ullman models problems and its development of solutions throughout the design process with the Task/Episode Accumulation (TEA) model (Ullman, Dietterich, & Stauffer, 1988). They use the state of the design and its operators to construct models of the design process. The design state is information about the changes within the design process. Operators are primitive modifiers of the design state. By forming a basic ontology of these items, design is modeled as combinations of operators applied in specific orders called episodes to the process. The information, state, and operators change frequently to develop the end solution. The number of operators, numbers of episodes, and number of tasks that can comprise a design process. By combining decision making, modifying entities, and descriptive states, this model of design processes can represent the current condition of a process, what is involved in the process and what is needed to change the process.

The TEA Models events that occur in design processes are tasks. They each have defined goals, which are accomplished on individual levels of detail. The information available in a design process is modeled to "accumulate" toward the ultimate final goal. Contributions from operators within the process model incrementally change the form or state of the existing problem and information. Each of the subordinate processes within a design process are called episodes and are completed individually, thus delivering the goals from each episode. Each episode and task is assigned a specific goal, which operators modify in order to achieve the solution. The TEA model shows the design problem state, operators that modify it, and the incremental changes that occur in the process.

2.4. The Systematic Design Process Model

Pahl and Beitz take a systematic approach to modeling design processes. Throughout the process, they track the formation and change of design goals, design tasks, and the design requirements that drive them. They consider four stages within the design process to establish overall goals for that selected group of entities. Each stage consists of functions which alter the state of some material, energy, or signal. The first of these stages is the clarification stage, in which effort is focused on properly defining the goals and establishing requirements that can accomplish the goals. The second stage is the conceptualization stage in which ideas are being formed. The functionality and requirements are decomposed in this stage to aid in creating solutions. Minimal concept evaluation is done in the ideation portion of this stage to promote a generative environment for the designers instead of prematurely eliminating ideas and hindering creativity. The third stage is the embodiment stage. In this stage, designers test, evaluate, refine, and produce artifacts that will become the final solution. Iteration within this step is common and encouraged in order to strengthen both the understanding of the problem as well as the solution used to address the problem. The final stage is detail design where the solution has been chosen, and limited changes are being made. Iteration at this point is not suggested unless it is critical because of the time required to return to the same point of in the process. The individual details of the artifact are refined here and all the required information is collected to be presented formally. Development, manufacturing, and installation instructions are created as the final step of the designer.

Throughout this process model, the requirements are continually changing to become more defined and complete. Each task executed is aimed at improving the requirements or accomplishing a goal, which then is used to refine requirements until the final solution is delivered. The Pahl and Beitz systematic design model is shown below in Figure 2.3. Notice the heavy use of staging sections for entities such as optimization, stages, and product state. This figure also shows the iteration possibilities within the systematic model and has an upgrade and improve loop that extends the length of the process itself. However, it is encouraged to iterate often and early rather than occasionally and late in the design process (Pahl & Beitz, 1995).

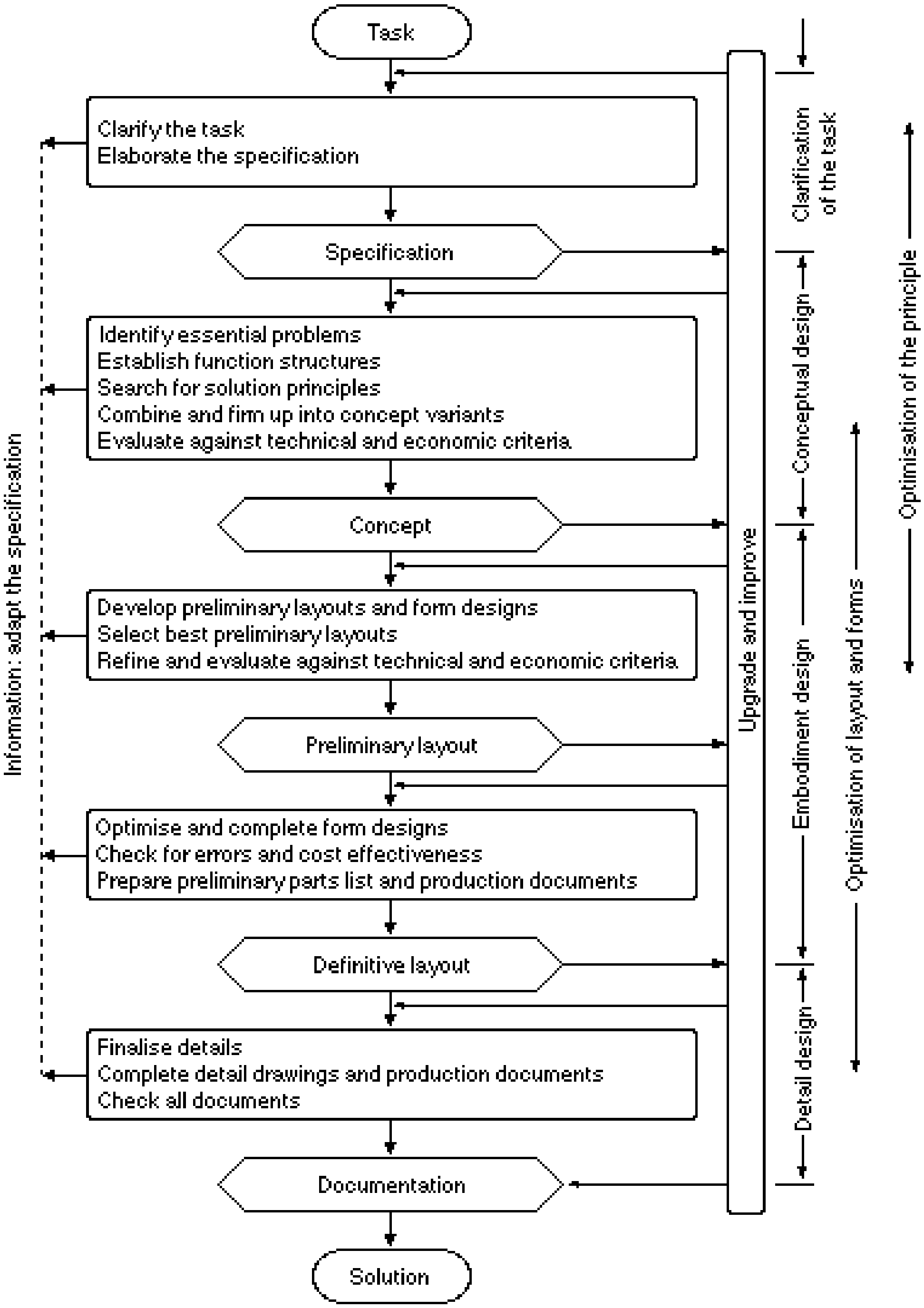


Figure 2.3: Pahl and Beitz's Model (Pahl & Beitz, 1995)

This model illustrates the design process effectively. It uses high level entities to populate the hierarchy which can be related to exact activities within the process. However, representing individual tasks of the process and individual tasks can be tiresome when using the existing high level classification. Pahl and Beitz actually use a graphic representation for the high level model, but magnifying the detail of the design process with such a representation would make tracking progress difficult. While the systematic model represents the over process well, it has limitations in representing process details without laborious effort to include details. Refer to (Pahl & Beitz, 1995) for more information on the systematic design process model.

2.5. The Clarkson Design Process Model

Change propagation is also used in modeling design processes (Clarkson, Simons, & Eckert, 2004). Clarkson et al. state that for existing products, changes must occur in order for a re-design to take place. Re-design is a form of design; therefore it is considered a design process which is what they have modeled. Change propagation is considered in this model to predict the expense and risk of changes that could be made to existing products by knowing some input design knowledge and requirements. The goal is to avoid risky and expensive changes while pursuing safe and beneficial changes. The change propagation model is shown below in Figure 2.4. It uses knowledge of the product domain as well as requirements to calculate possible product changes, therefore modifying the requirements and iterating. The arrival at a solution is accomplished by considering risk of change and selecting the appropriate change with the suitable risk.

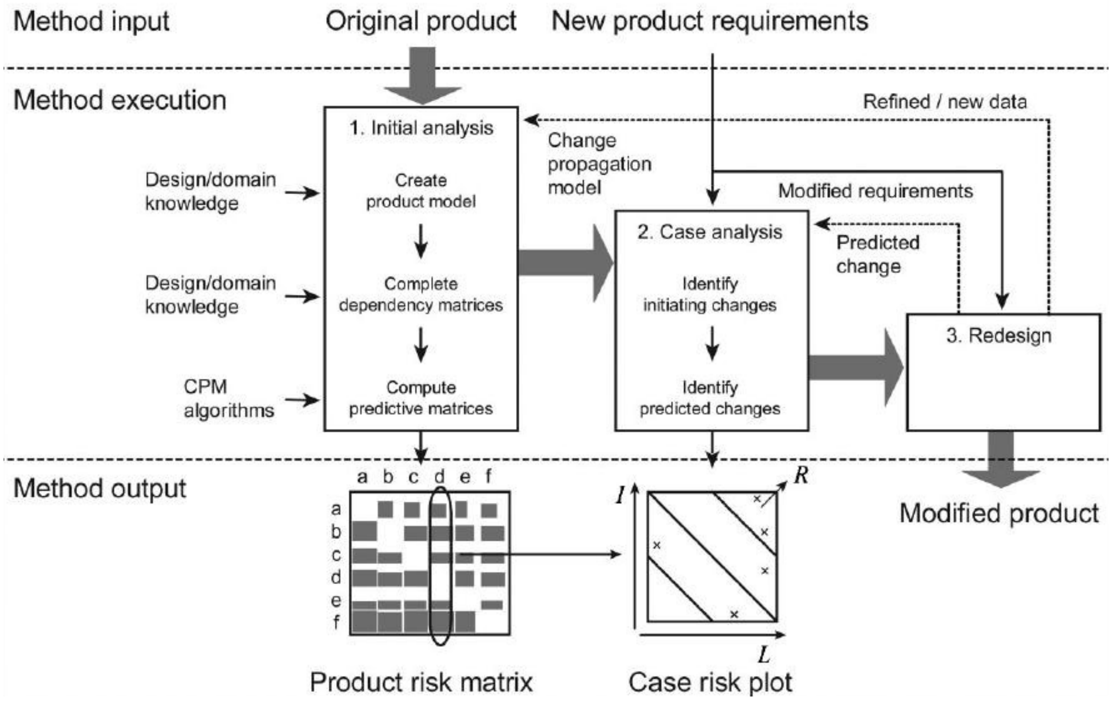


Figure 2.4: Change Propagation Model (Clarkson, Simons, & Eckert, 2004)

This design process model uses a significant portion of tabular representation to communicate to the designer what can happen. As shown above, this process model can be represented graphically and with sufficient clarity for the reader to understand the content. This model tracks the state of a product, information on the product, in the form of knowledge and requirements, and the changes made to the product, which generate the outcome product. The transformation occurs in the requirements and thereby the product. This occurs by sub processes in which work is done. Risk is also calculated and translated throughout the process model which helps in the re-design process. This model primarily calculates risk to changes that are potential, but does not promote generation of change ideas. Refer to (Clarkson, Simons, & Eckert, 2004) for more information on the change propagation design process model.

2.6. Decision Based Design Process Model

Decision based design is a concept which considers the design process to be a decision making process (Mistree & Marston, 1998). Based on this rationale decision based design organizes and assigns value to the options that exist within the design process so that the designer can make decisions in an educated and accurate manner. The goal is to enable the designer to make decisions that select the options which is expected to yield the highest value. This means that the options are evaluated and the outcomes of their use predicted, allowing the designer to select the option whose outcome best accomplishes the goals of the design process. The framework for decision based design can be seen below in Figure 2.5. It considers preferences, utility, and other design parameters such as attributes, demand, cost and exogenous variables to enable the designer to select the option which best satisfies the requirements of specific functions.

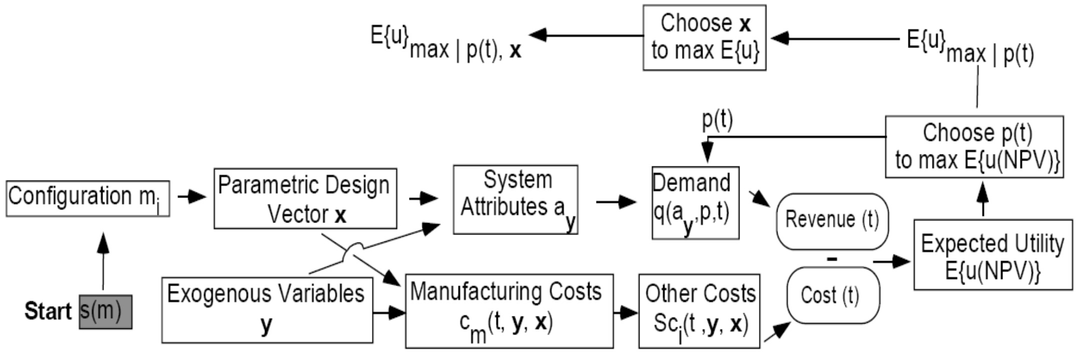


Figure 2.5: Decision Based Design Framework (Mistree & Marston, 1998)

Decision based design forms a list of options at every step of the design process. This bank is populated with the possible choices that the designer can make at the current stage. For each option presented, an associated risk and uncertainty exist, which must be considered before making a selection. Much like the change propagation model, decision based design allows the designer to evaluate the choices and make an educated selection based on the available options. Decision based design does not capture or process the ability to generate ideas or form relationships between design tasks and the products. This model of the design process focuses on engineering decisions and predicting the outcome that will occur if that decision is made. It does not communicate the ways design knowledge is generated or how it is altered, changed, and developed to become a design solution. Refer to (Hazelrigg, 1998) for more information on the decision based design process model.

2.7. Process Model Summary

In this chapter, the purpose and use of design process models has been discussed. Some of the various process models are tabulated in Table 2.1, showing the basic entity that is modeled and how each model communicates its information. Then some of the more popular models are discussed further, explaining how they work, what they represent, and how they benefit the designer. It was shown that throughout the various models presented, different information is represented and concerned by using that specific model.

Designers use these process models to enhance their understanding of the design process, and thereby improve their ability to execute design processes and arrive at a suitable solution. Each design process model was constructed with different contexts of application. Some track design tasks and some follow how information changes throughout the process. Many others exist, each having suitable use in performing some part of design. From the variations in model application shown in this chapter, it cannot be assumed that any single design process model can accurately and completely represent all of the information designers need when involved in design processes.

Thus, the ability to use any and all of the process models available is needed. Some researchers may use specific models often and never use others, but each model is used in some context, therefore proving it useful. In this thesis, no single design model will be chosen as the best option in representing design processes. Instead, a model will be generated that the researcher can represent other models and processes with. By having a flexible design process model, researchers can select the information that is represented and how the information is represented in context with the process. As mentioned previously, this model will be applied in representing case studies that the author participated in.

Chapter 3

REPRESENTING PROCESS MODELS

3.1. Visualizing Process Models

Visualizing the design process traditionally falls into one of a handful of formats. Each of these formats has benefits and limitations to its use. Understanding what each can and cannot do is critical to proper application within the design process model. Various design process models have already been discussed in the previous chapter and are not the topic here; rather visualizing these models is the focus of this chapter. Fundamental methods to presenting the information contained within design process models exist and are commonly used widely; IDEF0, PERT, and Network schemes are typically the most commonly used (Dorador & Young, 2000; Shenoy, 2000).

Representation schemes for design processes are methods which present the information contained in the model to the reader. However, not all design process models are represented similarly. Some are represented via text and others are graphic with some being capable of using both. Words can be formed and sentences constructed to that communicate the information needed (Nanard & Nanard, 1995). However, the task of producing such a document becomes tiresome. When reading, information that is not needed by the researcher is available and must be read for the entire document to be processed. A graphic model would allow more information to be communicated than descriptive text. A non-graphic representation would be something like a list or document which can contain ample information, but only what is intended by the creator. Should another researcher desire different information about the same process, it must be found elsewhere. Only the information that the author wrote in the document can be extracted. Images tend to include additional information which is not the focus of the content, but may still be of interest to some researchers. "A picture is worth a thousand words" means just that when describing complex processes. In the example below, the saying might better be said, "A picture is worth 428 words".

3.2. Graphic vs. Non-Graphic Representation: An Example

Below in Figure 3.1 an object is shown. The image has a uniform background and contains only the object and a scale. By observing the image, details of the information pertaining to the object can be communicated. Similarly, the information can be communicated via text in sentence structure, much like report writing and this thesis. The following paragraph describes the contents of the image in as much detail as possible.

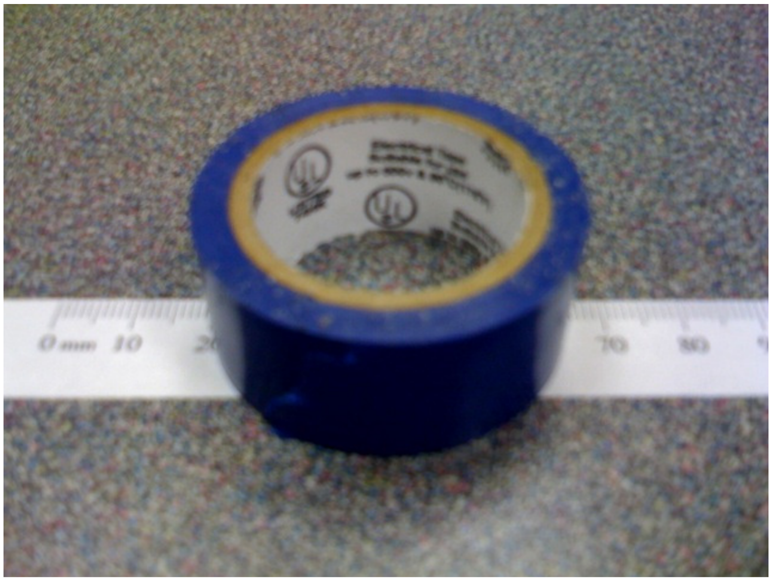


Figure 3.1: Graphic Representation Illustration

The object in Figure 3.1 is resting on a planar surface with mingled gray and black specks. Beneath the object lies a white scale with length units of millimeters (mm). The object's bottom surface is believed to be flat and thus, planar as it is resting on the planar table top. The object extends vertically some unknown distance approximated to be 15 millimeters. In the plane of the surface, the object has a cross sectional area similar to that of two different sized concentric circles. It is this cross section which extends vertically to another flat surface, parallel to that of the bottom. In effect, the object is a cylinder which is hollowed out, or a tube. The material of the object appears to be of two main constituents; a blue substance and a brown substance. The former surrounds the outermost surface of the latter. The brown substance yields no reflection, and appears to be fibrous. The inner surface of the brown substance is white in color and has black text printed around it's circumference on a diagonal with the horizontal plane. The text consists of a UL listed logo along with some tracking number and conditional usage information of the object. The text says, "Electrical Tape Suitable for use up to 600V and 80°C (176°F)". Another text block, also on a diagonal, has a different logo of the letters "SA" situated inside a larger letter "C". The following text also appears," Made in China Do not handle below -10°C suitable

> for use at not more than 80°C." The blue substance yields a satin reflection on the cylindrical outer surface. However, the top, and most likely bottom, flat surfaces are textured with circumferential grooves. Upon closer examination, these grooves appear to be edges of a membrane which is wrapped around the brown inner cylinder. The length of this membrane is such that the diameter of the object extends from the 20mm mark on the scale to the 65mm mark. This means that the cylinder is approximately 45mm in diameter. The inner diameter can be approximated to be 30mm yielding a tube thickness of roughly 7.5mm. The brown portion of the object appears to constitute one third of the thickness, meaning that the blue is roughly 4mm thick, in the radial direction. It can be assumed that the membrane is fitted with some sort of adhesive that causes the blue material to adhere to itself when wrapped in spiral manner around the brown tube. From this image, the object can be described as a blue roll of electrical tape.

As the previous paragraph shows, precise detail can be gained from text representations. However, some of the information presented is of little value or of too great detail for many readers. The complete information presented would rarely be of interest to anyone who is not a tape designer. Most people could be satisfied with the last sentence and have sufficient knowledge about the object. However, if given this multi-page document describing the object, the reader would need to absorb the entire contents and then communicate the critical portion to describe the content, “Blue electrical tape”. The act of pruning text documents is laborious, often enabling the editor to omit portions which may be of concern to specific parties (Tufte, 1986). Therefore, it is best for the researcher to read this report first hand, and remove text which they feel is not valid to the present work. Some text yields information that can only be communicated with text, such as the temperature rating of the tape. Any remaining text will effectively satisfy the needs of the researcher that trimmed the document.

This tape example also portrays the quantity of information that can be captured with graphic representations. The object was selected because of its simplicity, but could easily have been a much more complex object or system of objects, thus needing volumes of text for a full description. Despite the simplicity of this object, the resultant descriptive paragraph was over a page in length. While the text representation can give accurate and descriptive detail, the text is often lengthy and laborious to edit. Ideally, the detail will be maximized when writing the description, and then filtered after the reader has deemed a specific portion unnecessary (Lockledge & Salustri, 2001).

A graphic representation may or may not give the same explicit detail as a text document, but can allow the user to observe the information that is pertinent to their present work. This can greatly reduce both the size of the representation as well as the volume of information that must be processed in order to obtain the required description of the image. The tradeoff for graphic representations is that the visualization must be scaled properly to allow comprehendible representation of the needed detail of the topic.

This is still better than processing data that is not needed. This benefit is the reason that graphic representation of design processes is the goal of this thesis.

3.3. Graphic Representations

A variety of graphic representations exist, and each performs a specific function appropriate for its own use. Graphics such as diagrams, pictures, and icons are the most abstract. These have the least structure and can appear in almost any different form. They may be an actual picture taken of some scenery or a rendering of a specific item such as a logo. They can also be images which combine text with visual stimuli to communicate to the reader as shown below in Figure 3.2.

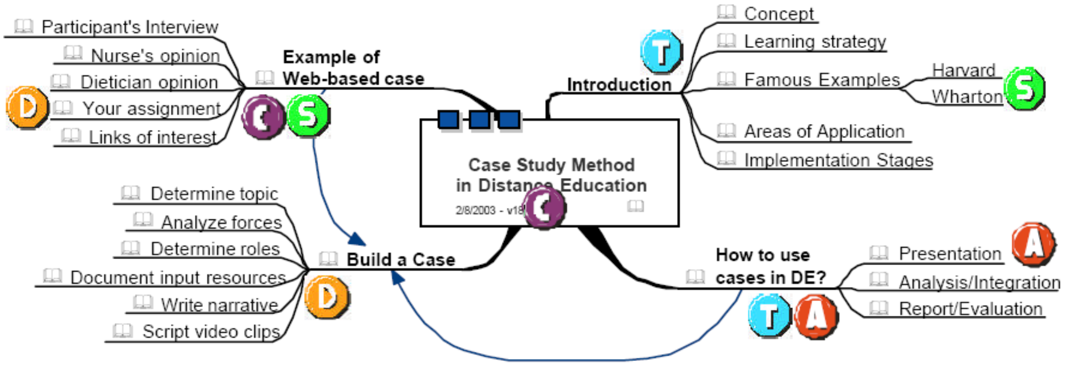


Figure 3.2: Example Diagram Representation (Chacon, 2003)

Other forms of graphic representations are charts, graphs, and plots. These often, but not always, relate directly to mathematical entities allowing great detail to be communicated in a relatively small form. Charts are typically used for comparison of few characteristics. Graphs and plots typically represent much more dense information populations, often of continuous expressions for the given domain. An example of such a representation is shown below in Figure 3.3.

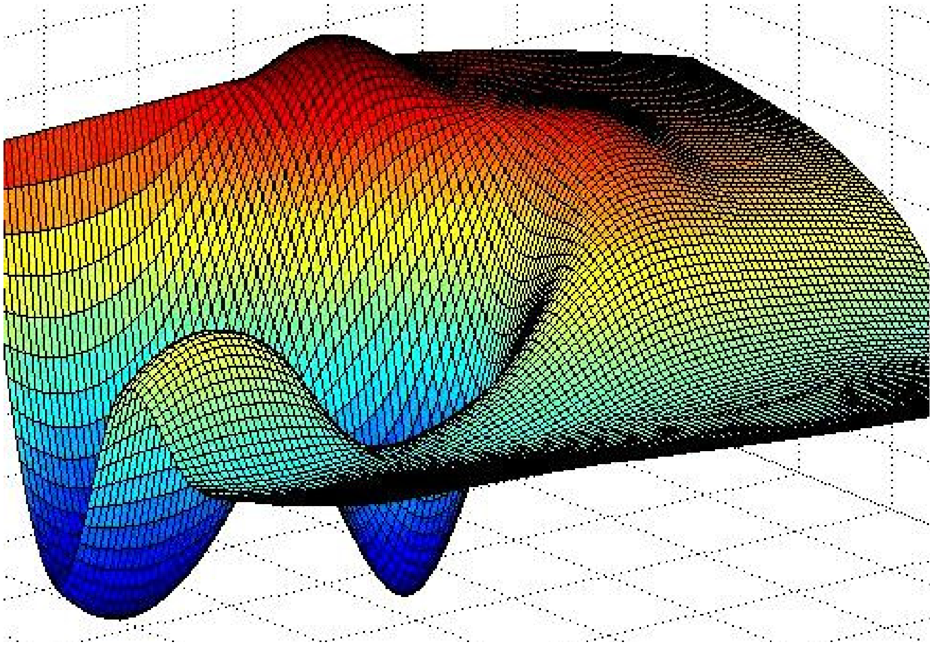
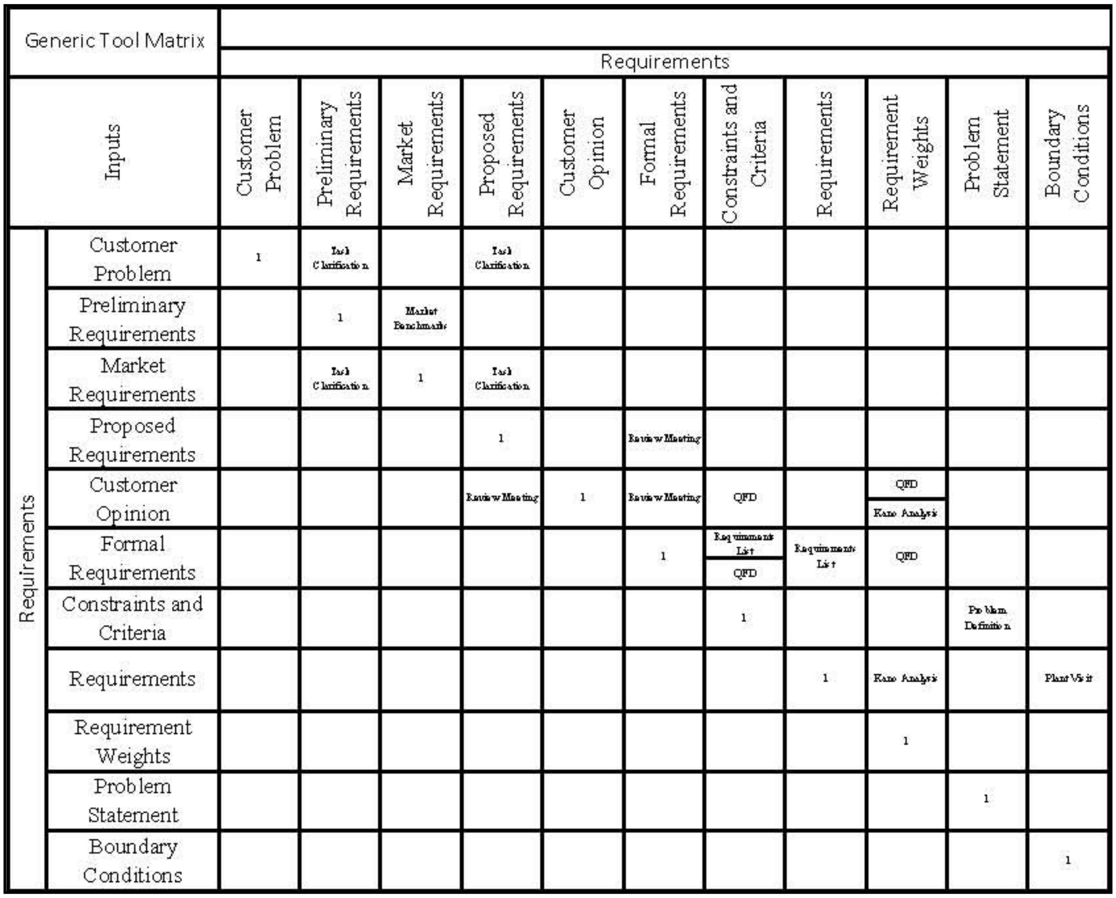


Figure 3.3: Example Graph Representation (Szymanski)

Matrix or table representations also utilize visual stimulus to communicate. However, these combine the visual principal with traditional text to relay information. Often, text is used in table headings, with symbols or numerical text occupying the data field. Understanding a matrix requires the reader to associate the row and column of the specified entity to the characteristics of that entity. This is an organized visual method, which includes the detail available from text representations. A sample matrix is shown below in Table 3.1.

Table 3.1: Example Matrix Representation



Generic Tool Matrix		Requirements										
Inputs		Customer Problem	Preliminary Requirements	Market Requirements	Proposed Requirements	Customer Opinion	Formal Requirements	Constraints and Criteria	Requirements	Requirement Weights	Problem Statement	Boundary Conditions
Requirements	Customer Problem	1	Task Clarification		Task Clarification							
	Preliminary Requirements		1	Market Benchmarks								
	Market Requirements		Task Clarification	1	Task Clarification							
	Proposed Requirements				1		Review Meeting					
	Customer Opinion				Review Meeting	1	Review Meeting	QFD		QFD Kano Analysis		
	Formal Requirements						1	Requirements List QFD	Requirements List	QFD		
	Constraints and Criteria							1			Problem Definition	
	Requirements								1	Kano Analysis		Plant Visit
	Requirement Weights									1		
	Problem Statement										1	
	Boundary Conditions											1

Since some text is needed to explain and enhance the detail of design processes, purely numerical graphs and plots are not suitable for design process representation. The remaining types are image, diagrams, and icons or tables and matrices. A tabular design representation has already been investigated and developed and is called Design Structure Matrices (DSM) (Steward, 1981). The purpose of DSMs is to show connectivity between design process components in a matrix grid. These components can vary in context from physical parts of an assembly to steps to a specific process. The matrix formed is used to visualize design fundamentals such as functionality, component interactions, or processing activities that exist between the components (Yassine, Falkenburg, & Chelst, 1999).

DSMs have valuable characteristics which account for their abundance in design research (Keller, Eckert, & Clarkson, 2006), but they also have limitations such as data density and output information format that prohibit them from doing things which other design process models can show. Above in Table 3.1 a generic DSM has been constructed. It is populated with assorted design tools oriented along the axes which represent the information input and outcome from that tool's completion. Note that a DSM of this size is unreadable in the format allowable in this thesis, therefore an abridged section is presented below, and the full matrix appears in **Error! Reference ource not found.**. The design tools shown are a collection of design tools and design methods. This thesis recognizes that the two are not the same but that their application and intent are similar, making the distinction between the two fuzzy and not critical to this work. Thus they will be collectively used in this case as design tools. The differentiation of the two will not be discussed due to the context and scope of this thesis. It is sufficient to know that each entity shown as a node is either a design tool or method.

3.4. Selecting Process Representation

A comparison of DSM matrices to an image diagram in representing design processes has been evaluated against design research criteria (Keller, Eckert, & Clarkson, 2006). In this evaluation, the DSM is compared to a Node Link diagram. Both of these methods are used to predict changes in process modeling and are a form of connectivity modeling, which Summers discusses in detail (Summers & Ameri, 2008). Visualizing processes is a form of preventative maintenance in process modeling. It allows the researcher to approximate the behavior of the process, allowing the current tasks to be modified so that the outcome is closer to what is desired (Clarkson, Simons, & Eckert, 2004; Hazelrigg, 1998). So in order to generate a method of representing design processes, a form of graphic representation must be selected; being either a matrix or node-link graph. This representation should allow the user to understand the information given with ease, and should be comprehensible both with and without computer assistance (Keller, Eckert, & Clarkson, 2006). Keller et al. has studied which of these two are better for certain criteria, and is summarized in the following paragraphs.

In evaluating matrices against node-link diagrams, measures needed to be established to give a level of goodness. The ease of locating a specific information unit or node is of interest. Likewise, identifying and locating a specific relationship, or link between two information units is also needed. The ability to count the number of links entering and exiting a node should be possible. The identification of any adjacent nodes should be available to the user with minimal effort. The tasks that determine goodness of the representations are:

- Selecting nodes
- Selecting links
- Count incoming links
- Count outgoing links
- Count adjacent nodes
- Identify shortest path between nodes

These six critical factors have been observed to significantly affect the usability of such a graphic tool. The size, density, and direction of the information contained in the graph are also considered since they all seem to affect how well the information can be absorbed (Keller, Eckert, & Clarkson, 2006). The size of data relates to the quantity of data that is represented in the process. For matrices, this is simply the number of rows times the number of columns. The size of a node-link diagram is the number of interactions between links and nodes within it. The density of such representations relates to the physical image that is generated and connectivity of the data to the rendered size of the total process model. The directionality of such representations relates to the direction of the links between each node. Links have a head and a tail, which simulate flow or the order of process. Perceiving this in the graph is needed for proper comprehension.

It was discovered that matrices lend favor to sorting information, thus aiding in selection (Keller, Eckert, & Clarkson, 2006). Matrices also allow linear searches of desired information, and can be sorted alphabetically to assist in locating specific items. Matrices are organized tables which can present large quantities of data in a clear fashion. However, matrices do make selection and counting of connecting links difficult. Identification of a relationship between two items is tedious to recognize meaning that identifying nodes adjacent to the current one is troublesome. Matrices also make following the path, or direction through the process difficult, as frequent row and column shifting is needed. Identifying the shortest process path via matrices is laborious if being analyzed manually.

Node-link diagrams present different benefits and challenges. They allow for identification of specific links easily. Determining the direction of the process links is easier with node-link diagrams, as is locating adjacent nodes. Following process paths is simple with node-link representations thus making the identification of the shortest possible path easy (Keller, Eckert, & Clarkson, 2006). The limitations to node-link graphs are the search ability and the need for graphic clarity. Matrices can be searched in a one dimensional manner by scanning either vertical or horizontal axis for the desired entity. Node-links exist in two dimensional areas, thus making searching more difficult due to the increased content that must be scanned in a search. Once a node-link diagram becomes somewhat large in data size, the image becomes cluttered with information, making understanding difficult. Keller et al. consider more than 40 nodes to be a large data set. Additional graphic clarity as well as image space is needed to properly show information to facilitate reading. Without proper spacing of node-links, the edges of nodes tend to cross and overlap which makes reading difficult.

It was determined that matrices are a better form of representing large quantities of data. A matrix can effectively organize all of the information of even the most cluttered and dense processes. However, when the quantity of data is low or moderate, node-link representations proved to be much more informative and efficient. If processes consist of fewer steps, and have limited connectivity, then a node-link can easily display the information to the designer. Organization is important to avoid information flow overlap and intersections whenever possible in node-link use. These reduce the clarity and therefore the readability of the diagram. The act of following paths, and shortest path identification were proven to be better represented with node-link diagrams for all datasets. This is believed to be due to the physical display of a path, which makes following easier.

Selection the best representation for modeling engineering design processes is the goal. Both, matrices and node link diagrams have benefits and limitations as shown in Table 3.2. The ability to follow information paths is of greater interest than an easy search method. The number of nodes and links in a design process model could also limit the use of node link diagrams.

Table 3.2: Node-Link vs. Matrix Comparison

Representation	Benefit	Limitation
Node Link	Path Following , Node Relations	Large Data Sets, Non-Linear Searching
Matrix	Linear Search , Large Data Sets	Path following , Node Relations

To determine the most suitable representation, the relative dataset sizes must be considered. Of the experiments performed by Keller et al., one was size ten, one was size twenty, and one was size forty. If design processes that are modeled consist of less than forty nodes, then it is suggested to select the node-link representation. However, if the number of nodes exceeds forty, a matrix representation is suggested as a more efficient representation. Since the path of information is of interest and of more importance than searching speed, a node-link representation is the proper choice. Therefore, if larger than forty node data sets are used, the size of the entire process representation should increase in order to allow proper detail of the information. Process path following is too difficult with matrices, and would limit the visualization of the process direction. Since path following is critical to understanding information generation, flow, and change, node-link diagrams will be used to represent design processes.

3.5. The IDEF0 Scheme

IDEF0 is used to model functions of a system (Dorador & Young, 2000). It represents the relationships and data which support the connection of those functions. The models are composed of hierarchal diagrams that show increasing levels of detail as the hierarchal level is reduced. IDEF0 is traditionally used to relate function to information of systems. The functions are traditionally shown as the nodes or entities. The information units or data which combine functions are shown as arrows leading from one function to another. A generic IDEF0 diagram is shown below in Figure 3.4: IDEF0 Node Illustration. In the image shown, the input is the incoming information. The control is the controlling operator, maybe a logic program or the designer. The mechanism is the design tool or entity used to complete the task, and the output is the product of the task.

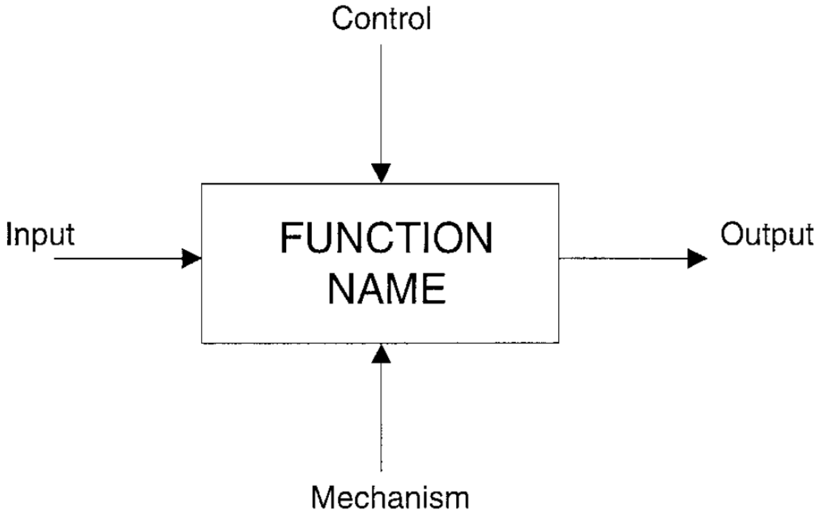


Figure 3.4: IDEF0 Node Illustration (Dorador & Young, 2000)

Per IDEF0 rules, only six functions can be shown on a single page at a time (Kim & Jang, 1999). This is for clarity purposes and restricts the amount of information so that what is presented is readable. An expanded IDEF0 diagram is shown below in Figure 3.5 and illustrates the complexity that can be generated from multiple functions existing on a single sheet. Notice how the predefined directions and spacing prevents specific links from standing out as more important than others. The flow of the information must be carefully traced along lines and around bends rather than directly to the link destination. Additionally, link overlaps tend to clutter the diagram space making comprehension more difficult.

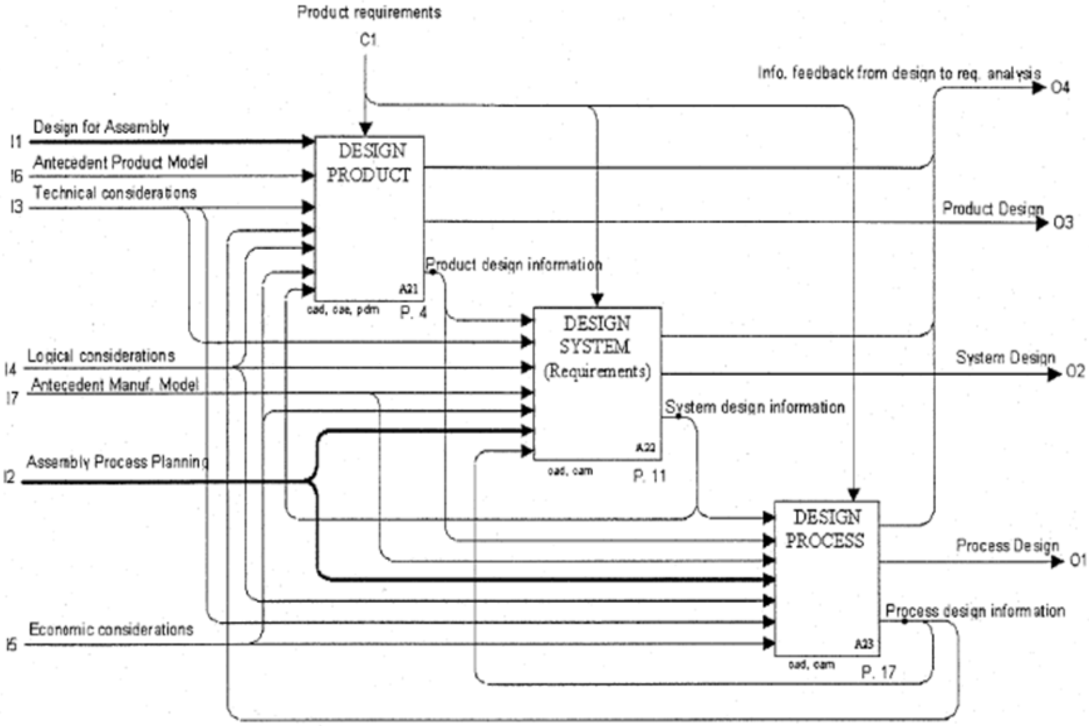


Figure 3.5: IDEF0 Expanded Example (Dorador & Young, 2000)

While IDEF0 diagrams allow designers to improve processes by describing critical information relationships, the traditional form of the tool is not optimal for representing process flows due to difficulty in tracking link flows. IDEF0 diagrams are suitable for showing activities and some connecting information. However, showing multiple domains of information flowing through nodes is something IDEF0 cannot easily communicate to the diagram reader. They present single domain information in an easy to comprehend manner that clearly shows the relationships with labeled inputs and products (Ahn & Crawford, 1994). The formal IDEF0 tool uses simple text to describe the entities within, and does not have the capability to show multiple information domains, nor alternate ways to illustrate those domains other than with text.

3.6. The PERT Scheme

PERT *(Program Evaluation and Review Technique)* is a project management tool which captures the domain of time for workflows (Pozewaunig, Eder, & Liebhart, 1997). PERT models activities, which are nodes, and their duration, which are the edges connecting the nodes. The duration of an activity within the representation is proportional to the distance from one node to another or the length of the edge. PERT represents processes as a collection, in series, parallel, or combination of both, of project activities. Unlike IDEF0, PERT is capable of relating specific events and activities to the time domain, thus enabling the user to more effectively manage the process by allowing scheduling evaluations to be completed alongside connectivity information. A sample PERT diagram is shown below in Figure 3.6: PERT Diagram.

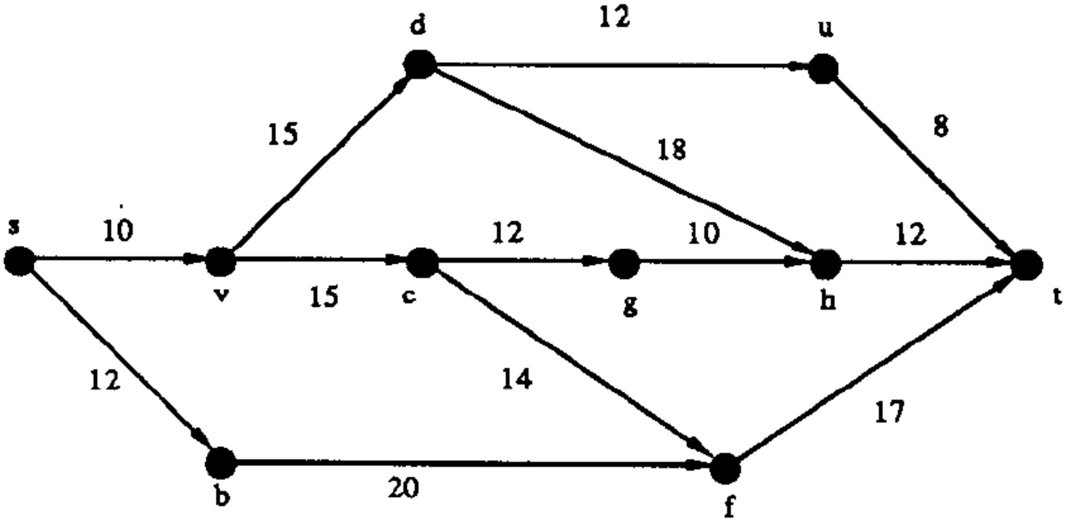


Figure 3.6: PERT Diagram (Battista, Pietrosanti, Tamassia, & Tollis, 1989)

PERT diagrams enable the user to instantly observe time relationships to workflow. Interpreting the information contained within PERT diagrams is easy and quick but the amount of information types contained is low, showing only event, connections, and time. PERT is traditionally used in a specific form, which narrows down the content to little text, and structured graphic nodes. The format of the lines and nodes are predefined which prohibits the user from assigning a specific characteristic in the diagram to another type of information about the process being modeled. For varying process representations, PERT could effectively show the time distribution of the tasks involved, but other information cannot be represented with a PERT diagram.

3.7. The Network Scheme

Networking schemes are representations that utilize graphic icons along with numerical text to communicate information about a process (Shenoy, 2000; Murdock, Szykman, & Sriram, 1997). They are a flexible and free form of representing a process in an efficient manner. They aid in representing multiple configurations of components that can accomplish a variety of purposes. Naturally, with the increase of content comes an increase of complexity and difficulty required to comprehend. A network representation is shown below in Figure 3.7. In this diagram, nodes of different shapes are connected via lines and arrows to other components, which are arranged in one of three lines. Each node is labeled with some variable notation representing another information entity about that node. The row of the node, shape of the node, label in the node, connection to other nodes, connection method and connection direction all representing different information domains about the components in this diagram.

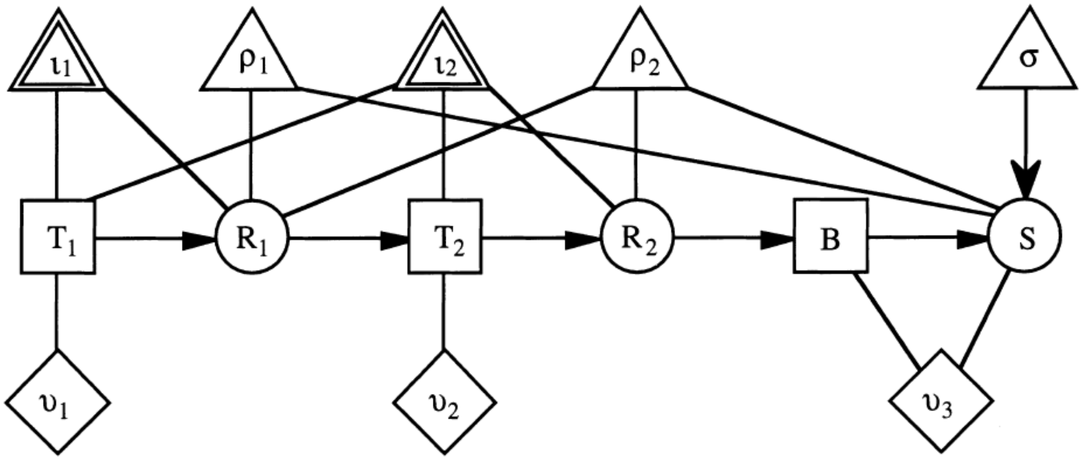


Figure 3.7: Network Diagram (Shenoy, 2000)

Network representations consist of qualitative entities which symbolize information as well as quantitative entities which relate the information to a specific value. They consist of nodes, that may be of any given shape, size, or color, to represent a specific entity. This may be a process, an event, a system or some other type of manipulator. Information enters and exits these entities via arrows that are directional. Additionally, network schemes have a layout that represents the hierarchy of the content, quickly showing some classification of the events taking place. Due to the pictoral format of network schemes that is required to illustrate hierarchy, clarity of data is sacrificed by allowing link intersections. Complex data populations can be shown with a network scheme, but the display of the hierarchy limits the ability of object layout in ways that do not cause link intersection in two dimension diagrams.

3.8. The Proposed Scheme

An ideal scheme would combine the beneficial qualities of each of these into a single representation that researcher can use to illustrate design processes. To accomplish this, a representation of information flow defined by the designer is in order. This would enable researchers to model processes with various information units without having standard information ontology that is currently unavailable but is being developed. The researcher should be able to specify the fundamental information of interest which is related to the specific information that flows through the process. The designer should also be capable of specifying the modifying bodies, or nodes, that exist so that the representation will be applicable to their specific area of work.

The goal is to be able to determine the appropriate steps and expectations of design processes given the available information. Figure 3.8 shows the appropriate mapping of real world information change which can be compared to the inappropriate mapping in Figure 3.9. Notice that using c*oncepts* in the Problem Definition step will not generate the p*roblem statement*. This should be representative of real world situations. The Problem Definition step cannot use *concepts* to generate *problem statements*. However, by completing the existing *problem statement*, a Brainstorming session can be completed, thus generating *concepts*. Since clarity is critical in modeling processes this way, the ways in which information is connected should be validated through application to familiar cases and then standardized for future reference.

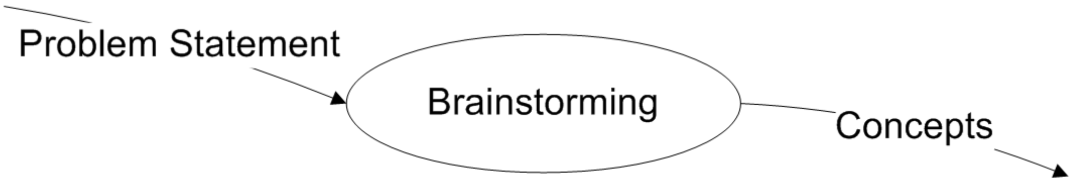


Figure 3.8: Appropriate Information Mapping

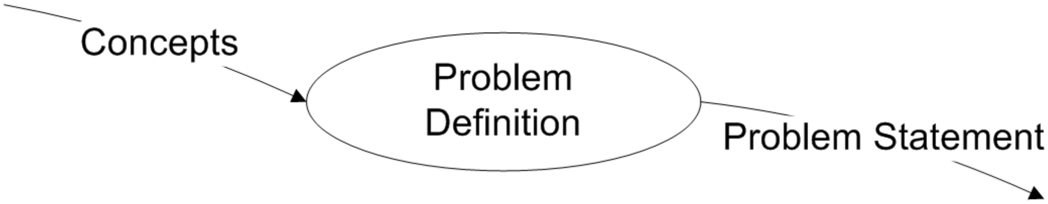


Figure 3.9: Inappropriate Information Mapping

Representing multiple domains of information should be possible with this representation. The use of text should be available but not required and should not be limited to specific formats. This allows the map builder the freedom to specify the ways each type of information is communicated, so long as the ways information is shown are not shared for multiple information types. This representation would be flexible to the researcher to use how each particular process needs it to in order to communicate the information that the designer desires to see.

Chapter 4

DESIGN ENABLER INFORMATION MAPS

4.1. DEIM Components

The graphic representation proposed is applied to three case studies to illustrate the benefit of case study use in design tool development. Through applying this suggested representation to the case studies, it is shown that DEIM allows researchers to create a visualization of design processes that can illustrate the needed information and be easily readable. By doing this, it is the goal of the representation to enable designers to understand, execute, analyze, and modify design processes in more effective ways than were previously available. By enabling design, the means of understanding, representing, modifying, and completing the process of design is permitted, or in this case, enhanced. Thus, this tool will be called *Design Enabler Information Map* or DEIM. Since information is the critical element of design, and the representation shows how information flows into and out of specific entities, these representations are called information maps. A generic information map is shown below in Figure 4.1.

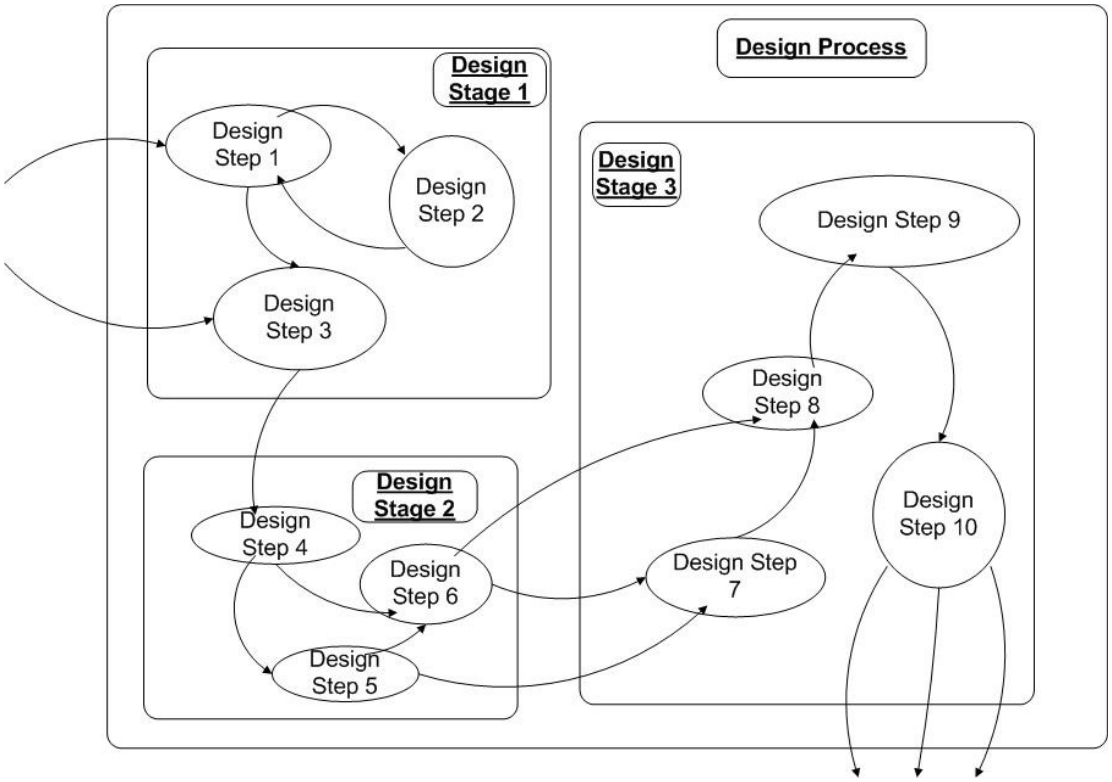


Figure 4.1: Generic DEIM

By intent, DEIM is to promote illustrative flexibility in what is represented as well as how it is represented for the case studies modeled. The main consideration when building a DEIM is to structure each connection in the context of what is being tracked, the information of interest. However, some formalism is required to enable logical perception by readers (Kim & Jang, 1999). To allow readability, the maps should flow downward and to the right starting at the top left corner. The ability to freely position nodes and links within the map remains, but the net flow of the process should extend from the top and left to the bottom and right of the map. Additionally, the method of representing information types cannot be shared by multiple types. These are requirements that permit the process to be modeled flexibly yet with organization.

DEIM's consist of a few components which are connected together to create the representation of the process. These are the information links, the accompanying nodes, and any specific borders which are an extension of the nodes. Information is represented in the form of arrow links, which may have specified thickness, color, line style, length, labels, and direction (Kim & Jang, 1999). The nodes can consist of various shapes, sizes, colors, and labels. Any graphical property of the maps can be defined as a characteristic key of the map, thus representing some specific information unit. Borders shown within DEIM perform the same function of nodes, establishing detail limits to the investigation of the process. Borders are shown on the highest level as the design process boundary allowing initial information to enter and the solution information to exit. However, boundaries can be established not only for stages of the design process, as shown, but of any organizational purposes needed.

The representation formed resembles IDEF0 closely. The main difference is that IDEF0 has specific restrictions which have been lifted for DEIM. For example, the number of nodes on a page can only be six in IDEF0 format. With DEIM the researcher is free to place as many nodes as possible on the pages. The clarity of the map may be sacrificed, but this is a decision of the mapper. In later sections, it is demonstrated that full length processes can be represented via DEIM with sufficient clarity for information tracking. IDEF0 also accounts for the Input, Control, Output, and Mechanism of each function. DEIM is only concerned with the Input and Output to reduce effort needed to properly classify information and shift focus to modeling the process.

Each component in DEIM represents some sort of information that is important to the overall representation. Information links represent the most elemental component of the process representation. These may be explicitly information units or could be generic information with uniform characteristics. The nodes represent the transformation of the information from one state to another. These can be sub-processes beyond the level of detail of the map or could be tools used to modify the information. The borders that exist in the DEIM are expansions of higher level nodes. They serve to group information links and action nodes of specific relation together. The list below describes the steps of constructing a DEIM.

4.2. Method for Constructing DEIM

1. Define the initial problem.
2. Determine information of interest. (links)
3. Define the scope of the problem.
4. Determine Included Information Sources
5. Establish Level of detail
6. Determine the entities of interest. (nodes)
7. Incrementally connect links to nodes

4.2.1. Define the initial problem

To start a DEIM, one must first establish the initial problem statement. This will most likely be an ambiguous, high level question that contains un-needed information as well as missing critical information to the design process. The benefit of applying

DEIM to case studies is that these wastes and insufficiencies can be illustrated for examination. In most cases, the initial problem statement is the problem as defined by the client of the designer. This must be taken, analyzed for information content, and most likely reworded to better describe the intended solution (Ulrich & Eppinger, 2008). The goal of this step is to establish the context of the information that is to be mapped with DEIM. This context will be used to maintain focus when mapping information flow throughout the process.

4.2.2. Determine information of interest

The item of interest to be tracked throughout the design process should be established next. Generically, this is information. While information can serve as an appropriate transitional element throughout the map, more detail can be used to represent what is flowing. Some examples of this might be design process documents, such as reports, lists, spreadsheets, and graphs that are generated and can be used as the design process progresses. However, a generic "information" entity will allow the mapper to capture information without being confined to a specific type of entity being tracked when the specific information flowing is not of interest to the mapper. As mentioned previously, the combination of design tools and design methods is an example of this generalization. The two are different in nature, but have similar intent which allows the generalization to communicate without concern of semantics for the definition.

4.2.3. Define the scope of the problem (Information Sources)

The scope of the problem must next be defined. Researchers will often find this part difficult to properly constrain. Information sources as well as level of detail must be established in this step. Information sources serve as inputs to the transformation of information through the acting bodies of the map, the nodes. Specifying the concerned information sources is effectively giving a limit to the domain of the map. It does not negate the value or existence of the incoming information, but rather borders the area of analysis for the researcher.

It can be assumed that the requirements of a specific market come from some sort of market research, which may or may not be included in the design process. If the researcher chooses not to include this research, then the information needed will enter the design process as an external information entity, rather than be generated within its boundaries, thus the market research would be out of the scope of the process as shown in Figure 4.3 rather than in the scope as shown in Figure 4.2.

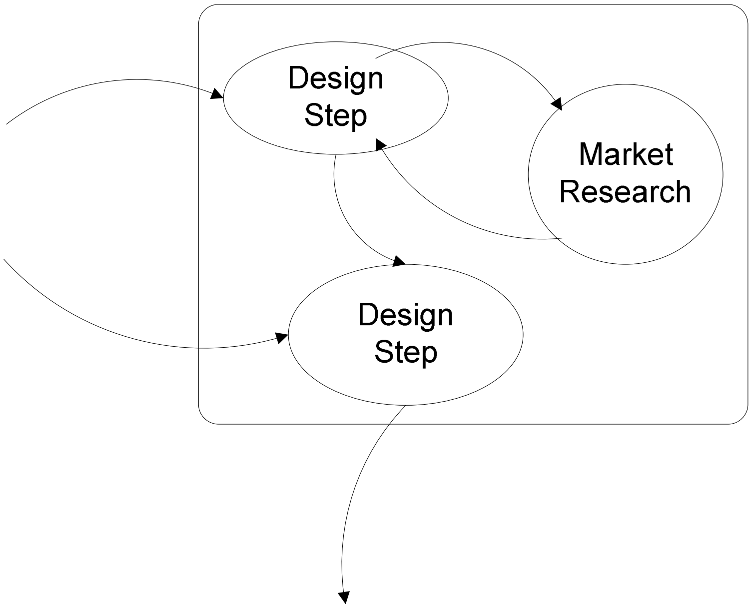


Figure 4.2: Market Research in Process Scope

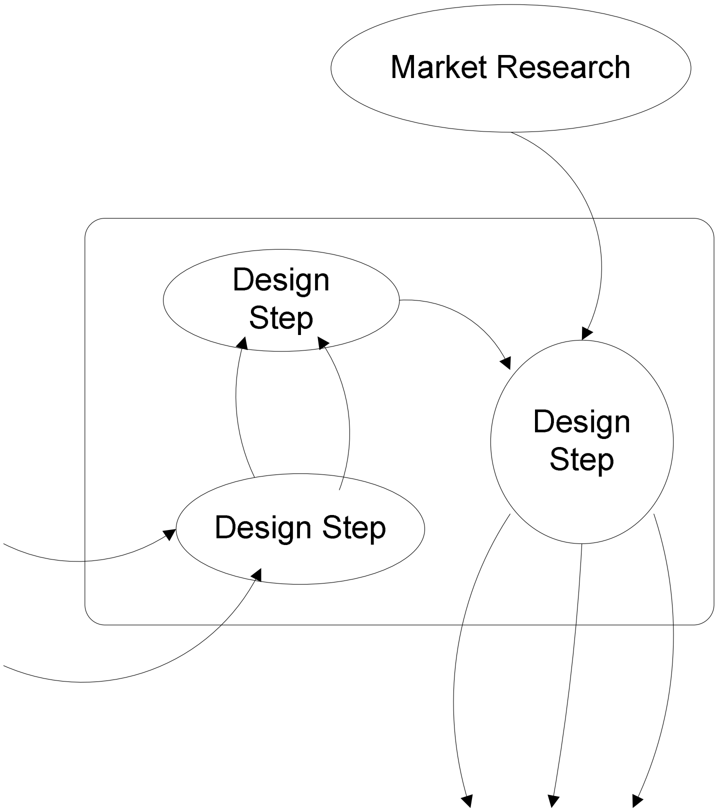


Figure 4.3: Market Research out of Process Scope

4.2.4. Define the scope of the problem (Level of Detail)

Similarly, the level of detail must be determined. Other graphical representations such as IDEF0 establish the level of detail on incremental levels by limiting the amount of information available on a single page (Dorador & Young, 2000). DEIM has a resolution of detail prescribed by the mapper. This is done by developing a rudimentary hierarchy of the information being represented. To be uniform, the level of detail represented by the information links should be equivalent for each link shown.

For example, in Figure 4.4 a hierarchy is shown that consists of horizontal hierarchy levels. For this figure, if the information of interest was “Market Research Documents” then entities such as “Testing Results” and “Loaded Deflections”, entities on a lower hierarchy level, would not be shown as they are beyond the level of detail for the process. However, if the information of interest were “Presented Design Solution” then “Loaded Deflections” and “Testing Results”, both in higher levels of the hierarchy, would be shown in the map as well.

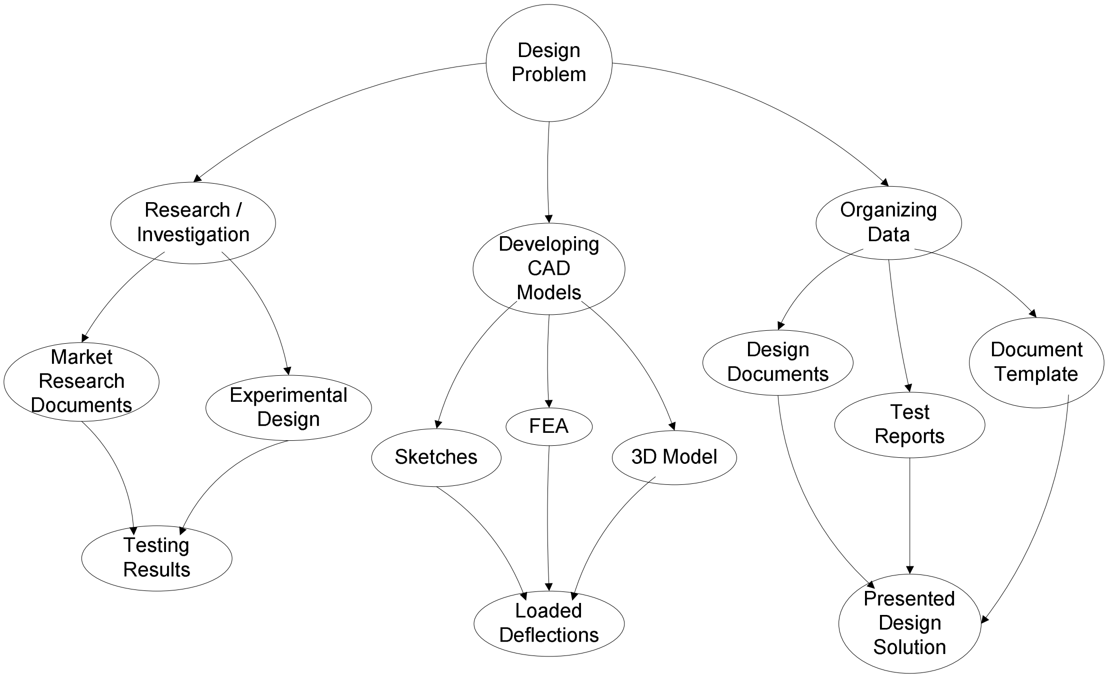


Figure 4.4: Process Information Hierarchy

4.2.5. Determine the entities of interest

The next step is to establish a translational entity, the nodes of the map. The examples shown in Chapter Five combined design tool and design method as the nodes. To determine what the appropriate node for any given map should be, the link's characteristics should be considered. The node must be an entity which alters the form of the link. As discussed previously, the node must combine, separate, or transform the link information. Based on current experience, the best way to determine what the node should be is to evaluate what is done or used to progress from the existing link state to the next appropriate link state.

An example of this can be illustrated with the Requirements List in Figure 4.5. This is a list of goals the design product must accomplish, and is a formally recognized design tool. In order to progress from a Requirements List, the tool must be used through some process or step in order to start generating ideas of solution concepts. This is traditionally done by decomposing the functions of the problem (Pahl & Beitz, 1995), which requires a function decomposition to be executed. Function decompositions are design methods, compared to a Function Structure, which are design tools that are generated by the function decomposition. Function Decompositions are the appropriate node to transform the Requirements List to a Function Structure.

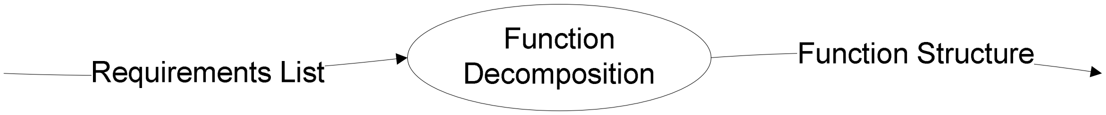


Figure 4.5: Function Decomposition Input and Deliverable

4.2.6. Incrementally connect links to nodes

The connection of the known links to their altering nodes then takes place. It is at this step that the cognitive work of the researcher must begin by deciding exactly what is done with the first unit of information received from the client. Applying DEIM to represent case studies adds significant benefit in this step. By taking part in the design process, the author was able to recall the events that occurred, the order in which they occurred, and the information that was developed by the event. By applying DEIM theory to the known cases, the construction of, and evaluation with DEIM can be validated.

Most design processes will initiate with some form of task clarification sub-process. By doing so, the researcher investigate the design space to establish what can and cannot be considered within the design process. No matter what the initial information is, it must be connected to a node which; a) can accept that information as an input and, b) be used to generate something other than the input information. Therefore, the need of an information and design tool ontology is justified.

The same applies to each following step when constructing a DEIM. When directing information to a specific node, that node must lead to other information that is different from its entering condition. This can be done by the mapper or researcher adding cognitive "work" which is a topic by itself and will not be discussed in this thesis. Nevertheless, the addition of work to the entering information creates more information whose value is greater than that of the sum of its components. This fundamental phenomenon can also allow multiple information entities to combine within a sub-process to generate new information that can then be channeled to other steps within the process (nodes). Similarly, certain information units can be separated into more elemental parts, which then exit to separate nodes.

Constructing a DEIM is easiest done after the design process is complete. Constructing DEIM in real-time would give the designer a specific awareness that could benefit future steps of the process. If the researcher builds a DEIM after completion of the process, historical recollection can serve as a vital asset to connecting information links and is often easier to do than concurrent DEIM construction. This is the approach taken in this Thesis by the application of DEIM process modeling to the case studies.

The goal of constructing a DEIM is to sufficiently track the initial information given to the designer through each step it is transformed through until the desired exiting information is reached. This will allow the designer to understand how information changes, how information flows, and how information is related to specific operations within a process.

Iterations within processes can be captured and represented with DEIM. These are represented by steps producing information which returns to a previous step that supplied information to the prior step. Often, iterations will repeat more than once. A benefit of DEIM is that the researcher decides how this is represented. This flexibility allows the mapper to select a representation method that suits the information and will not make the map difficult to read. Multiple links are used to show the number of iterations taken for one of the case studies. Clustered numbers are also used in the other DEIMs. Other graphic sources, such as link width could also be used to illustrate the number of iterations taken within the process, if that was desired. Color coding the links to pertain to specific numbers or utilizing line styles to illustrate to number of repetitions can also be used. Sometimes, a simple expansion of iterations is suitable, showing each loop of the process iteration separately. Illustrating information such as the number of iterations in processes is where DEIM allows the researcher to increase the information in the representation. Some examples of iterative maps are shown below in Figure 4.6.

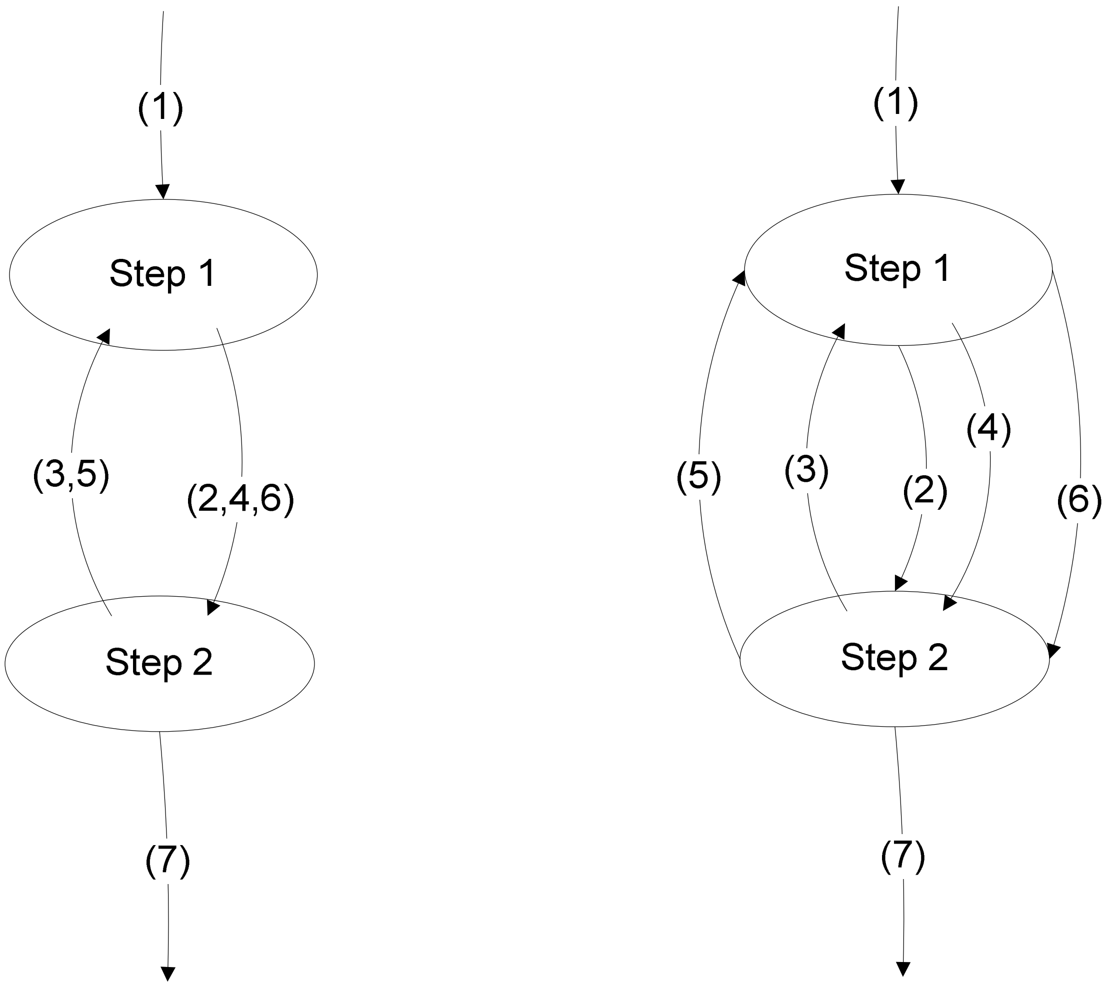


Figure 4.6: DEIM Iteration Labels

Much like the ability to specify the way iterations are shown in DEIM, the researcher also has the capability to relate any specific visual property of DEIM to desired information. An example of this can be the geometric location and spacing of the nodes. Closely grouped nodes signify a specific designer's responsibility from a team of designers in one of the case studies. The other case studies group nodes according to the specific stage of design which the node exists in. The mapper has the ability to prescribe all of these characteristics. The important thing to remember is that the coding should remain uniform throughout the process map, but not necessarily between different maps.

The following precautions need to be observed when building DEIM. The mental mapping of information through processes is easy to misrepresent. During construction, it is easy to show information being generated from a node, when it was actually generated by other means. Care must be taken to ensure what is being mapped is actually what happened within the design process. The best way to avoid problems in this respect is to use a team of researchers to build the DEIM in which each person constantly critiques the validity of the other's insight to the process. This helps to properly represent the process by using subjective opinion from multiple perspectives. The nature of building DEIM allows misrepresentation to exist and remain without check. During DEIM constructions, events are forgotten or overlooked. Information is represented as coming from a specific node when it actually came from a different node. These errors are unintentional, but part of the human nature of the mapper. An iterative evaluation of the process representation is critical to accurate development of the DEIM. When a process is represented, it should relate to specific ideas, documents, events, procedures, and tools that were involved in the actual process. This often reveals information not included in the map as well as information that are represented inaccurately. Iterating the construction of a DEIM allows the mapper to refine the representation, therefore making the creation of DEIM much easier after the process is complete. Uniformity of representation must also be observed. If the line thickness of a link represents a specific unit of information, it must represent that same information for the entire map, therefore making the needed ontology part of the map legend. Altering the representation for information codes will make the DEIM confusing to read and allow inaccurate comprehension of the process, thus proving the need of map standardization.

DEIM can be used to represent actual complex design processes, consisting of a multitude of information domains, and including an assortment of active entities which work together to illustrate a design process in a clear and concise manner. The information contained within a DEIM can be low if the mapper desires, resulting in a DEIM showing a single type of information throughout the process. Additionally, DEIM can show many different types of information while still remaining readable by the user. Ultimately, they show what happens in a process as well as how it happens by illustrating the connectivity and transformation of links through nodes.

Chapter 5

DEIM DEMONSTRATION

5.1. Testing the Theory of DEIM

To test the use of and verify the benefit from DEIM, three design projects were represented using the DEIM method in a manner similar to Hernandez et al. used in validating their case study work (Hernandez, et al., 2001). The author was involved with each of these projects thus lending firsthand experience to the events as they occurred, giving the author the ability to map the events of the design processes into DEIM. These DEIM models were constructed after the project was complete, although the time span between project completion and map development varies for each example shown. Table 5.1 below compares the logistics of each case used.

Table 5.1: Case Study Comparison

	EAI	**WMP**	**Michelin**
Duration	24 Months	4 Months	14 Months
# of Participants	6	6	8
Review Frequency	4 Weeks	1 Week	1 Week
Professors	1	0	2
Graduates	4	0	5
Under-Grads	1	6	1
Deliverable	Revised Vehicle CAD	New Work Cell	New Equipment and Testing Procedure
End to Map Time	5 Months	20 Months	1 Month

For each of the examples shown, the information link will be generic design process information that may range from Requirements Lists to Concept Performance.

The nodes selected are the combination of design methods and tools and are found in Appendix B. As mentioned previously, the author recognizes the difference in these two, but for this thesis, the distinctions are not of interest, therefore they will be used collectively. These serve to transform the information from its entering state to some other form via work.

In these maps, several generic design stages exist such as, Clarification, Ideation, Selection, and Refinement. These were chosen based on Pahl and Beitz's systematic engineering design process (Pahl & Beitz, 1995). Each respective map may or may not show the explicit stage boundaries, depending on the type of work being done. An example of this is the EAI project which consisted of three separate and concurrent detail refinement stages. The baler, trash compactor, and structure systems all were designed independently, at the same time. Rather than show a single refinement stage, the EAI map shows each separate system refinement stage of the design process.

5.2. The EAI Project

The *Environmental America Inc.* (EAI) project was a privately sponsored endeavor. The company, EAI, had an idea to patent and prototype an integrated recycling center on board a common trash collection truck. EAI approached designers with a fourth generation prototype and asked the researchers to "streamline" the truck by reducing cost, mass, and complexity. This project relied heavily on the task clarification stage of design. Significant work was done to justify implementation of such a product into the infrastructure of local cities and residual plans had to be made that would affect the performance of the end product. Once appropriate justification of such a device was found, work began on ideation of concepts and product breakdown. The fundamental requirements of the truck were developed and used to eliminate excess systems on the current prototype. Once certain systems were eliminated, work began to improve efficiency and performance of the needed systems to conduct the truck's tasks. This work was segmented into three areas; Trash collection, Baler Design, and Structure Design (Smith, Johnston, & Summers, 2007).

The first of these is the design of the Trash handling equipment. This involved conceptualizing equipment to compact the trash and eject the load once at the land fill. The investigation of how trash behaves when compressed became difficult, thus the boundary conditions and loadings generated by such actions could not be simulated when analyzing. Current market examples were researched, but proved to be over-designed and therefore were too large to fit in the allowable space on the truck chassis. Significant difficulty was encountered in modeling the behavior of trash, therefore, the project funding ceased before sufficient information about this could be collected.

The baler design was more productive. Again, loading and boundary conditions were needed for the baler design and analysis. To gain this information, tests were conducted and data was collected on how to model the components of the balers. Once this information was secured, the CAD models could be developed and analyzed properly to extract useful results. The testing phase of this design proved instrumental in the generation of both concept ideas and Loading Conditions for the simulation.

The superstructure design was also completed. Instead of testing, specification information was gathered from benchmarking existing vehicles and reproducing the functionality of those designs. The safety of the concepts was checked via FEA and the loadings gathered from market research. This package was delivered on time and is currently under production.

The DEIM of the EAI project was completed five months after the design project was finished. The old design documents generated during the project aided in recalling the tasks that were performed and the order in which things occurred. The DEIM representation of the EAI project is shown below in Figure 5.1. For clarity, a larger version of the map is also in Appendix C. The information links vary in content but are primarily generic process information. Notice that each of the nodes is a design tool or design method which was used to transform the information to some other form. The line style of the node signifies what that node is. A bold node outline represents formal design tools. A thin node outline represents an informal action which can possibly be a design tool or method. Finally, the dotted outlines represent a fuzzy definition of that particular node. For these, the intent may be common, but the way in which the action was taken may constitute some modified version of a standard task definition. Thus these types of nodes are classified as "Fuzzy" and shown with a dotted line.

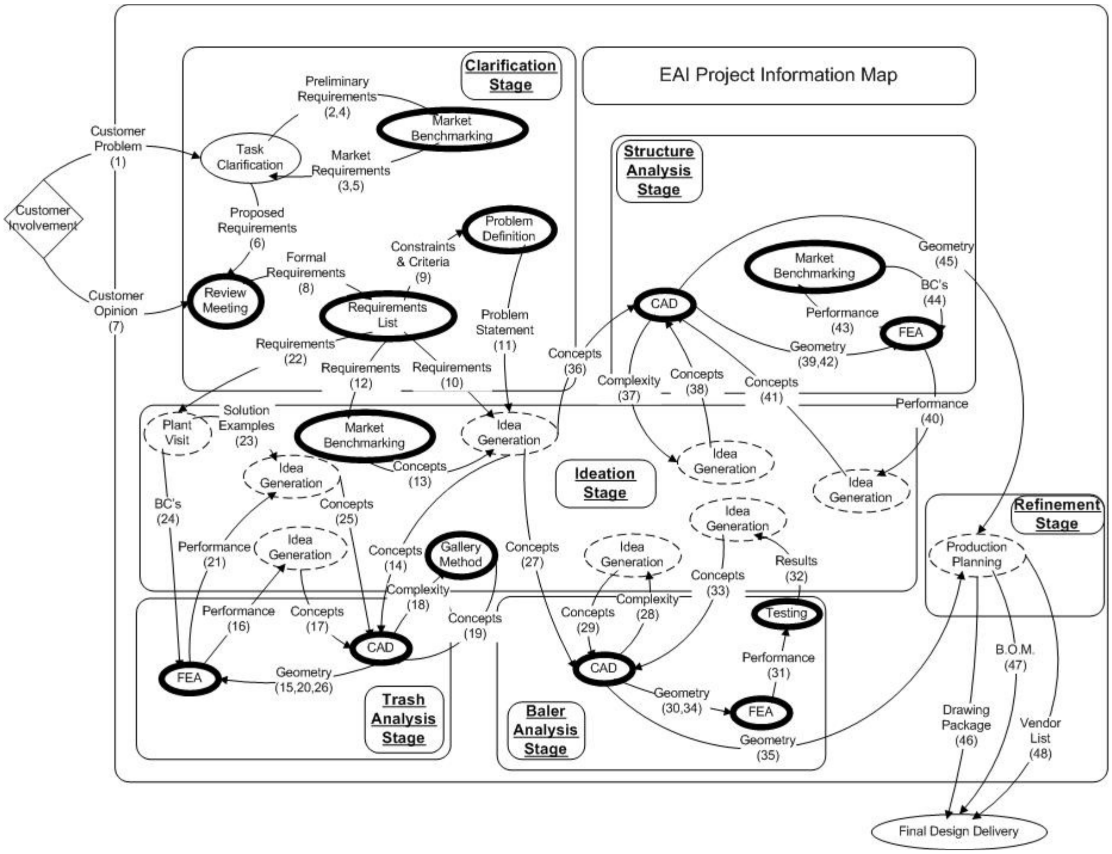


Figure 5.1: EAI DEIM

For this example, the information links can be related back to physical design documents or files. The Requirements List is a document that was printed and presented to the client. The *geometry* generated from the CAD step is the *.prt* file for each respective part that was then analyzed in FEA. Note that this project ended when the drawing package and other manufacturing documents were presented to the client. This is because the client had means to manufacture the truck within their company; therefore the plans were all that were needed for production to start, thus defining the scope of the model.

While examining the DEIM for the EAI project, certain clarity issues are revealed due to the format limitations of this thesis document. Therefore, a larger version is presented in Appendix C. Additionally, this model of the EAI design process can be compared to a companion process representation, DSM, to illustrate the clarity of DEIM over DSM for modeling complex design processes.

Table 5.2 is the EAI design process represented in DSM format. Again, it is shown in Appendix D for the clarity of a larger format. It can be seen from comparing the two that the DEIM does promote information path following much easier than the DSM. Additionally, for the low number of links which exist, (48), the ability to follow information paths as well as observe process flow with DEIM is higher than with the DSM. The DSM does allow a linear search and identification method, but since this design process can be represented with sufficiently small transitional entities, the node link based DEIM is more suitable for showing node and link connections and information flow throughout the process.

Table 5.2: EAI DSM

EAI Tool Matrix		Requirements										
Inputs		Customer Problem	Preliminary Requirements	Market Requirements	Proposed Requirements	Customer Opinion	Formal Requirements	Constraints and Criteria	Requirements	Requirement Weights	Problem Statement	Boundary Conditions
Requirements	Customer Problem	1	Task Clarification		Task Clarification							
	Preliminary Requirements		1	Market Benchmarks								
	Market Requirements		Task Clarification	1	Task Clarification							
	Proposed Requirements				1		Review Meeting					
	Customer Opinion					1	Review Meeting					
	Formal Requirements						1	Requirements List	Requirements List			
	Constraints and Criteria							1			Problem Definition	
	Requirements								1			Plant Visit
	Requirement Weights									1		
	Problem Statement										1	
	Boundary Conditions											1

In the EAI DSM, the same information from the EAI DEIM is shown. The vertical axis represents information inputs while the horizontal axis represents information generated with the name of the design tool or method appearing at the intersection of the appropriate row and column. For example, it can be seen that by using "Formal Requirements" as input information, the "Requirements List" can be used to generate "Constraints and Criteria" as well as "Requirements". While the DSM is clear, discovering that these two information entities are connected to "Requirements List" would require column and row identification as well as searching for other links which may enter or exit the "Requirements List" node.

It can be seen that DSM can represent complex design processes as well. However, the ability of DSM to show information link and design tool node relationships is lower than that of DEIM. The required information can be attained by following rows and columns and identifying the appropriate headings, thereby relating those information titles to the tool node selected. This is considerably more laborious than observing arrow titles entering and exiting a node with DEIM. For this reason, DEIM is more effective at communicating node link relationships than DSM. It is important to note that the amount of information is not different, but just the effort required to collect it.

The following section consists of a description of each transitional element within the EAI design process. The map has been modified to illustrate the location of that section's topic. The initial client information is what starts the process, and cues the first transforming action to take place. For each node of the map, the information that enters and exits the node is described. The process by which the transformation took place is then described along with the actual design tools or design methods that were implemented during the transformation process.

5.2.1. Task Clarification:

The first step accomplished was the Task Clarification activity, Figure 5.2. Designers took the initial *customer problem* and researched the infrastructure, market, and systems that would be involved in the design. After clarifying their task, the engineers would compare the *preliminary requirement* against similar model benchmarks in existence. By performing market research, additional market requirements were established and used to feedback into the task clarification stage in order to define the most effectively project *requirement.* This process was repeated several times, shown via the iteration labels. Each time the *requirements* gained more detailed information about what would be needed for the design. This design activity would produce a formalized list of *proposed requirements* that must be achieved by the design solution.

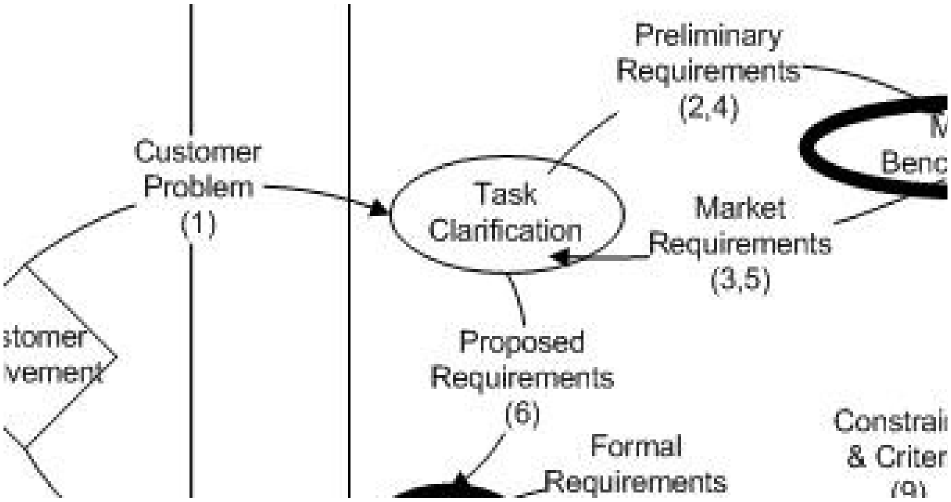


Figure 5.2: Task Clarification Node

The Task Clarification step of design first requires interaction between the client and the designers. Then the designers perform research to verify assumptions and conditions that the client is involved with. Using this information, the designers then investigate the existing market concerning their products. Throughout the process, additional information is revealed and added to the growing list of *requirements* for the project. After searching the market for similar products, the designers then formalize all the information they have gained into a *proposed requirements* list. Studying each requirement is needed to properly state its characteristics in a detailed and complete list.

The activity or design tool completed is an informal one, not having any defined method of execution or process. If formal Task Clarification tools exist they could have been used as an alternate to generate the same *proposed requirements* list. At this point, the ambiguity of the node definition arises. Some nodes are formal design tools. Others are formal design methods. They can also be design activities or more generically, steps. From now on, these definitions will be used interchangeably, although their definitions are all different. The overall intent with their use is uniform and accomplishes the representation needed.

5.2.2. Market Benchmarking:

The Market Benchmarking process was used to compare the current problems to actual cases in order to examine the completeness of the requirement's detail. Shown in Figure 5.3 , this activity took the *preliminary requirements* from the Task Clarification stage and used them to determine other market needs that were not met by the *preliminary requirements*. This additional information was fed back into the Task Clarification stage iteratively, each time refining of requirements. The Market Benchmarking step is also used later in the design process to comparatively generate *boundary conditions* for FEA as well as to generate *concepts* for Idea Generation. It accomplishes this by using the analysis *performance* and the *requirements*.

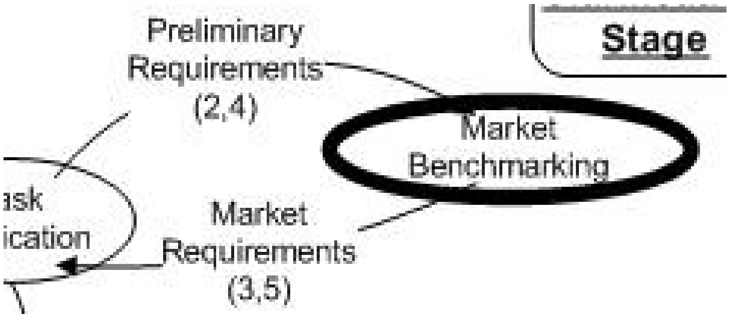


Figure 5.3: Market Benchmarking Node

The Market Benchmarking step was conducted by examining current examples of the products that the designers were to create. These examples ranged from cardboard balers, to car shredders, to steel I-Beam dimensions. Some of these were examined by making phone calls to vendors which can be considered a means to the function of this high level node. Others were investigated by visiting manufacturing facilities or dealerships to take measurements and operate the machinery which can also be considered a means to achieving the purpose of the node, benchmarking the market. The goal of this step is to learn more about what is being designed to a point where a successful new product could be fully defined by the outcome of the Task Clarification step, the *requirements*. By using the market benchmarks, the designers were able to find out what already works, and what can or cannot be done in designing the product. This step consisted of no formal design tools for completion because no formal examples were known to the designers during the project. Instead, it consisted of Internet search software and telephone calls.

5.2.3. Review Meeting:

The design Review Meeting activity, shown in Figure 5.4, served as a milestone to formalize the design *requirements*. The designers took the *proposed requirements* and allowed the *client* to review them. Discussions clarified the meaning of several *requirements*, and some were eliminated or altered. Once both the engineers and the client settled on the *formal requirements*, they were used for the remainder of the project. These requirements are used to establish the goals of the design team throughout the design process.

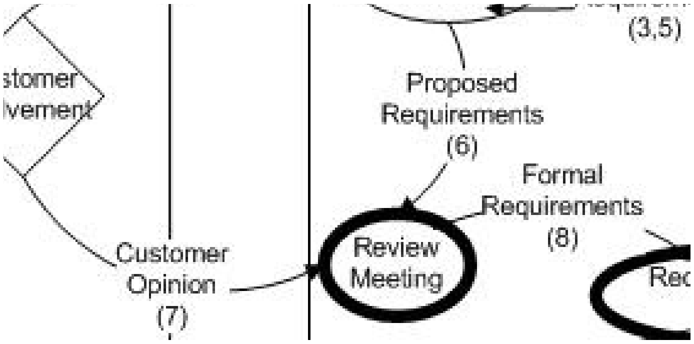


Figure 5.4: Review Meeting Node

In order to have a review meeting, the designers formed a presentation and/or report which documents the suggestions of the designers. During the meeting, these *requirements* are presented to the client. They are explained, and discussed along with the supporting research findings. Once all of the *requirements* have been critiqued and approved, they are listed and used as the *formal requirements* of the project. Formal design tools for this project were not used, although the Review Meeting was a formal event. Again, document and presentation software packages were used to present the work of the designers in a professional manner.

5.2.4. Requirements List:

The Requirements List step, shown in Figure 5.5, is used to organize the *formal requirements* approved in the Review Meeting. This list uses those *requirements* to feed as idea generation guidelines in the Idea Generation, Plant Visit, and Market Benchmarking sessions later on in the design process. The *requirements* are developed into a list of c*onstraints*, which must be achieved for project success, and *criteria*, which are desirable characteristics of the design project. Having *constraints and criteria* ranks the significance of the *requirements* to a degree which aids the designer in assigning value to the specific requirement of interest. Organizing the *requirements* allows the engineer to further understand the design space of the project. It allows the designers to know what type of systems and components would be needed to successfully complete the design project.

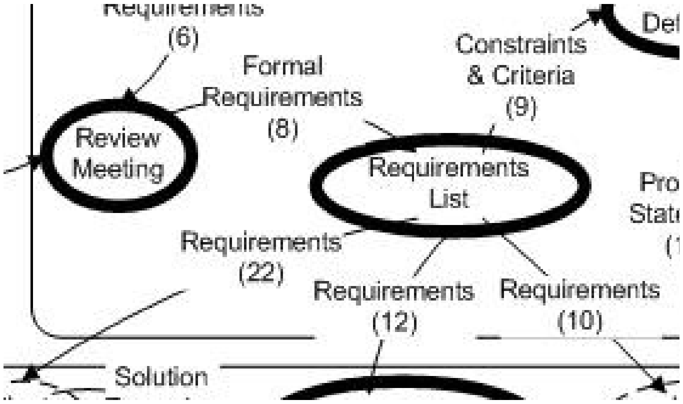


Figure 5.5: Requirements List Node

To form the Requirements List, the designers take the *formal requirements* agreed upon in the Review Meeting, and decompose each of them into proper hierarchal statements. They are worded and posed properly to pertain to the context of the design problem. Out of this analysis, the *constraints and criteria* are generated. The Requirements List also allows channeling of the *requirements* to proper steps of the design process when needed. For this project, the *requirements* are used in the Idea Generation Steps, therefore the *requirements* flow from the Requirements List into the Idea Generation Step, as shown. For this step, a formal design tool was used; a Requirements List. This is a universal method of organizing information so that completion can be determined.

5.2.5. Problem Definition:

The Problem Definition stage, Figure 5.6, served as an organizational tool to generate a thorough and accurate statement of purpose for the design process. This step took the *constraints and criteria* from the Requirements List and translated them into a *statement* which fully described the components and functions comprised by the system. The Problem Statement that was generated was used to describe the goal of the design team throughout the process.

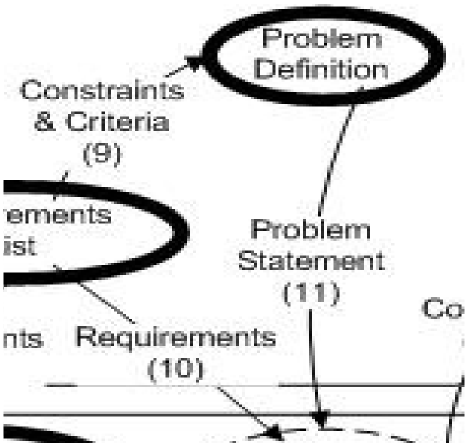


Figure 5.6: Problem Definition Node

To create the *problem statement*, the designers formed the Requirements List into a statement which contained sufficient information to accomplish each of the *requirements* mentioned. This step essentially forms a sentenced structure paragraph out of a List of Requirements. The work required comes from the designer to understand the *requirements* sufficiently enough to form flowing sentences describing them. Problem Definition is a formal design tool used to organize efforts toward a single objective, the Problem Statement, thus completing the Clarification Stage of the EAI design process.

5.2.6. Idea Generation:

The Idea Generation step, Figure 5.7, of this design process proved to be the most connected of all the activities performed. This design tool utilizes a variety of inputs to generate conceptual ideas within the Ideation Stage of Design. Inputs such as *requirements problem statements*, *performance ratings*, *test results*, *concept complexity*, *solution examples*, and *concepts* were used within the Idea Generation step to generate feasible *concept* ideas. Studying this step shows that while many different types of inputs can be used to execute the Idea Generation process, only idea Concepts can be produced from it.

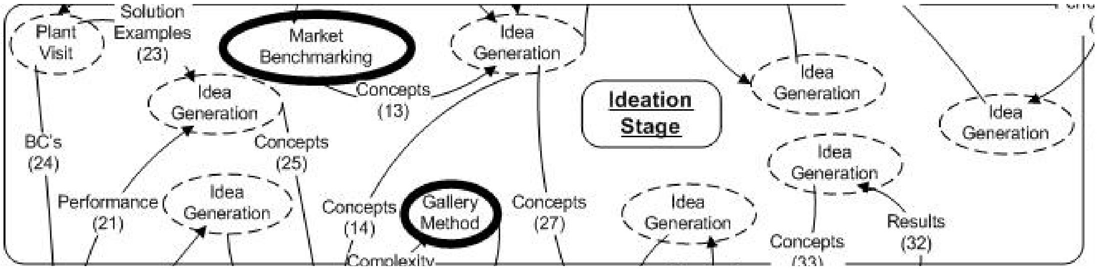


Figure 5.7: Idea Generation Nodes

To execute the Idea Generation process, the designers utilized no formal Design Tools. Some could say that what the designers did was brainstorming, but that is defined as done in a specific timeframe with a specific number of participants. The EAI designers utilized a random Idea Generation method. What they did was similar to brainstorming, but it will not be called that for technical reasons. The Idea Generation done for the EAI project was completed knowing the *requirements* that needed to be accomplished by the design process. The group focused on the individual requirements, and generated possible solutions to each. After a sufficient number of ideas were formed, some filtering occurred to present the most logical and probable ideas for further development. Many times, the Idea Generation step took place as a second or third iteration of the design process. In these cases, the Idea generation step also included the performance feedback from previous concepts so that proper ideas could be converged upon during the generation process; however this is not shown on the EAI DEIM.

In the EAI map, it is easy to see that the Idea Generation step of design was the most involved and complex one used. For this map, the Idea Generation step was fully expanded to show each repetition of its use. This level of detail drastically enhanced the understanding enabled by the map, but also took significantly more effort to produce. Notice how any design step with “loops” or multiple inputs and outputs can be viewed this way. For this map, only the Idea Generation step was done in order to show the value added from, and the additional work required to produce this visualization.

5.2.7. Plant Visit:

The Plant Visit stage, Figure 5.8, of the design process was an organized tour of the manufacturing facility of the trash compactors. This was done to give the designers better understanding of simulating trash behavior in compaction. By knowing the design *requirements* the designers could observe the compactors in action to generate *solution examples* for Idea Generation purposes. Additionally, by measuring specific things at the plant, the designers could develop *boundary conditions* to use in the FEA step.

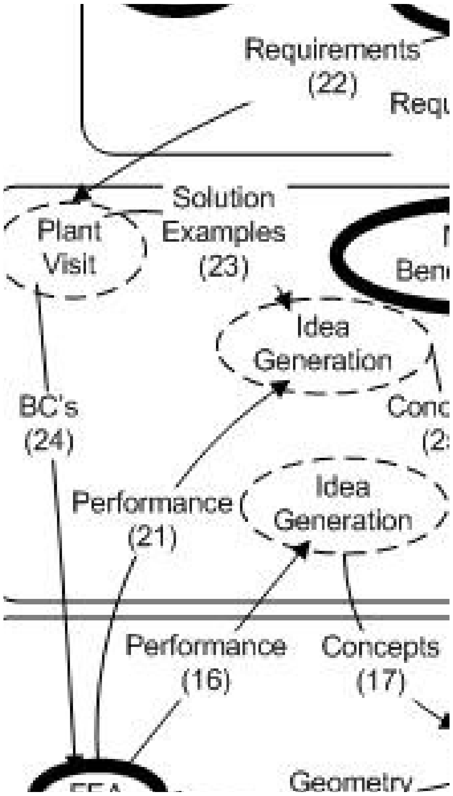


Figure 5.8: Plant Visit Node

This step of the design process was completed by calling the manufacturer and arranging an appointment for the tour. The designer then traveled to the location and was allowed to see how the compactors were made, and how they operate. Specific models were available for testing, and the designer was allowed to take measurements and operate the machinery. This is not a formal design tool, but proper data collection could be organized into a defined tool which enables designers to observe and collect small quantities of information.

5.2.8. Gallery Method:

When the designers were involved in the Gallery Method step, Figure 5.9, they were attempting to generate concept ideas which would position a functional trash compactor of sufficient size on the truck chassis. Knowing the complexity of the concept, the designers completed the Gallery Method exercise in order to develop additional concepts which may accomplish the goal of the design process.

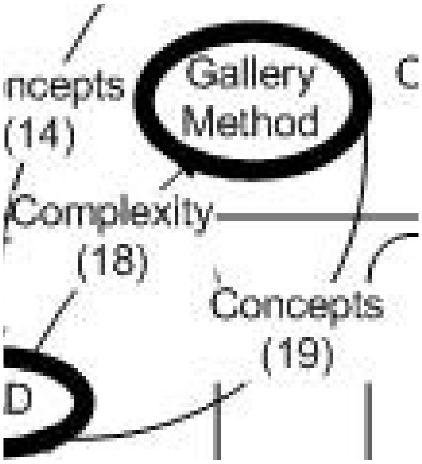


Figure 5.9: Gallery Method Node

The Gallery Method step was completed when the designers organized a meeting and discussed the problems of the current concepts. They then began sketching solutions to parts of the problem, and the entire problem. These were displayed to stimulate the other designers in generating more solutions, but no discussion was held. This is a forma design tool which is used as a purely idea generative method to problem solving. Other Idea Generation alternates, such as Brainstorming, and Method 635, exist and could have been used instead of the Gallery Method (Pahl & Beitz, 1995).

5.2.9. CAD:

The CAD step, Figure 5.10, Figure 5.11, and Figure 5.12, of the EAI design project occurred on several different systems. These are the Trash Compaction, Baler Analysis, and Structure Design, as mentioned earlier. For each of these CAD steps, *concept* ideas from the Idea Generation steps were formed into 3D CAD models. Examining these CAD models allowed the designers to converge the designs to something that could spatially and functionally work. This iteration was driven based on the *complexity* of the CAD models generated. Once a CAD *geometry* that looked logical was formed, it would be entered into FEA for a performance evaluation. Often times, the *performance* ratings of the design would feed into the CAD step, prompting another model to be generated. Ultimately, when the CAD model was sufficiently verified, it was use to generate the *manufacturing documents*.

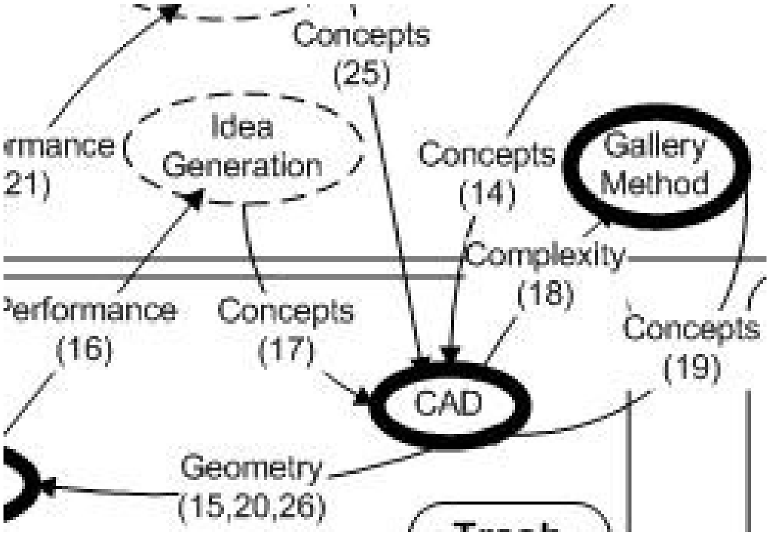


Figure 5.10: Trash CAD Node

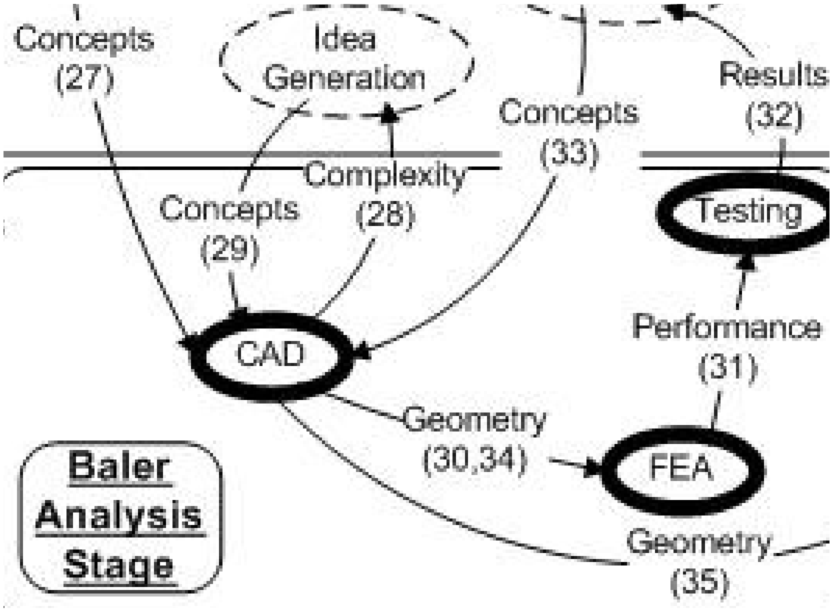


Figure 5.11: Baler CAD Node

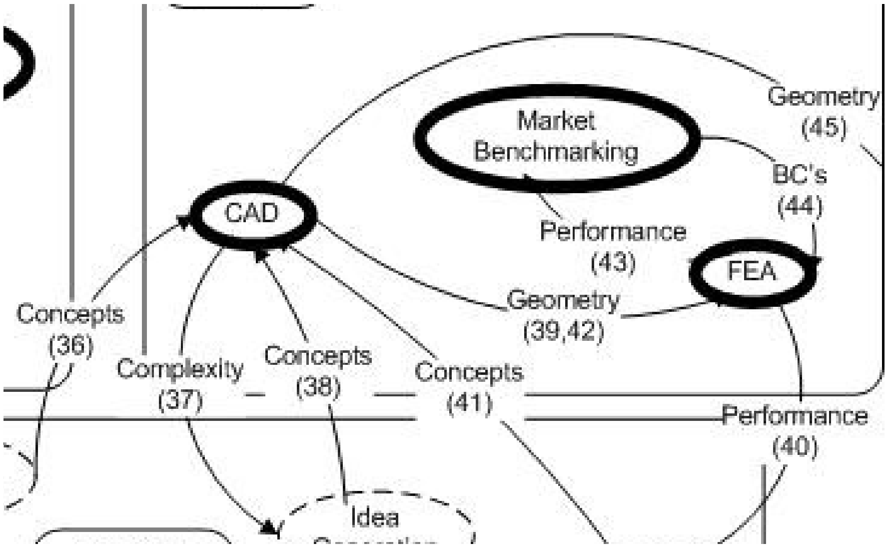


Figure 5.12: Structure CAD Node

The CAD step consisted of designers developing CAD models from concept ideas. These models were checked for fit, function, and finally, strength. Once a concept passed each validation, the *geometry* was used to form the deliverable documents to the client. This is a formal design tool, thus allowing the designer to access many advanced features and options in its use. The CAD step was not required, however developing the final plans, validating designs, and checking component fitment would have been difficult without the use of virtual space.

5.2.10. FEA:

The FEA steps of the project, Figure 5.13, Figure 5.14, and Figure 5.15, took considerable time. Due to the size of some of the CAD models, the analysis computers would be operating under full load for extended periods of time. The FEA step took the *geometry* from the CAD step and combined it with the known *boundary conditions* to generate a report of the strength of the *concept*, *performance*. As shown, iterations of this step did occur, meaning that analysis of some subsystems was repeated multiple times. Pending the results of the FEA *performance*, the concept would then be ready to finalize via CAD, for delivery.

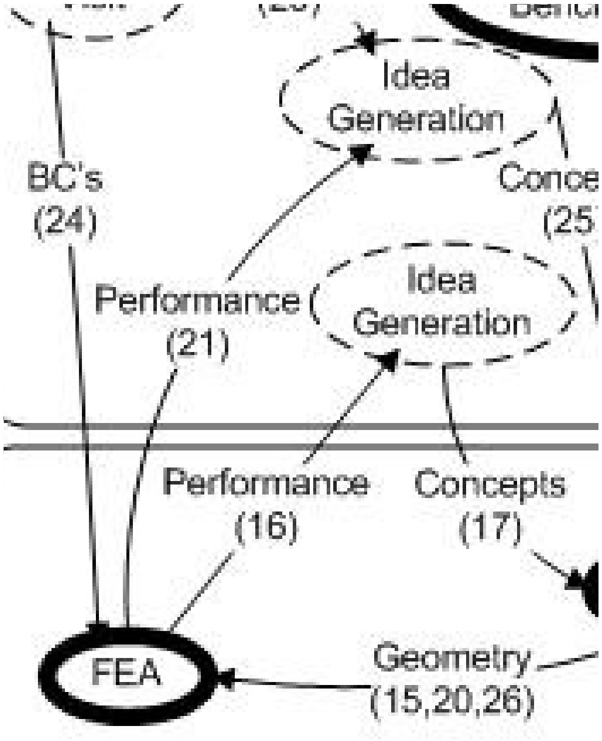


Figure 5.13: Trash FEA Node

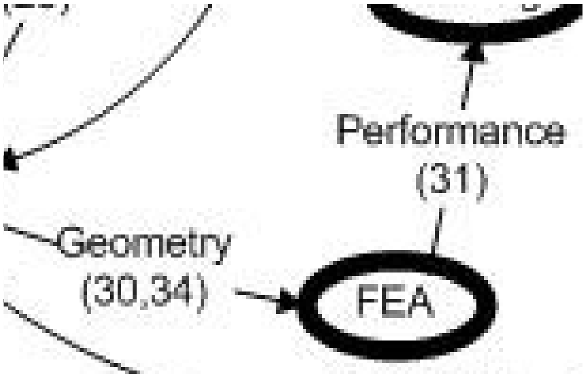


Figure 5.14: Baler FEA Node

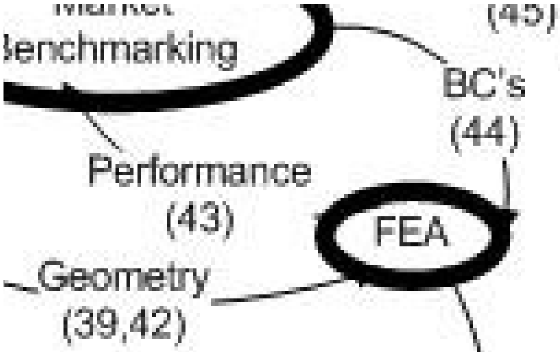


Figure 5.15: Structure FEA Node

The process of FEA is a formal design tool to engineers; however it is a lengthy and laborious one. For the EAI project, designers completed the FEA step by applying *boundary conditions* such as loads and fixations to CAD models and numerically analyzing the stresses, strains and deflections that result from the conditions given to the models. If the results were not satisfactory to the designer, the *concept* or loading condition was modified and the analysis repeated. Again, FEA was not required for completion, but validating the design concepts by hand analysis would be impossible due to time constraints.

5.2.11. Testing:

The Testing step of the EAI project, Figure 5.16, was used to relate the *performance* of an invalidated FEA model to real world results. The deflections and loads applied in the FEA model were recorded and compared to the deflections and loads measured from real world examples of the baler. The FEA model was then modified until the loadings gave the measured results that corresponded with the measured real world examples. This step was used to validate the *results* gained from the FEA step and ensure that *results* were accurate.

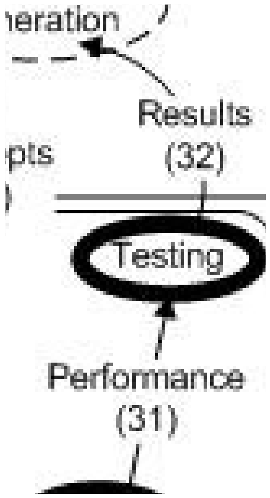


Figure 5.16: Testing Node

The Testing step was completed by running initial FEA simulations. The results from that analysis were used to compare to measured deflections of a sample baler that was located. Strain gages and micrometers were used to measure the baler wall deflection under load. The *results* were recorded and compared to that of the FEA. The FEA loadings were then changed to more appropriately simulate the baler situation. When the analysis was reiterated, the *results* coincided with those found from the experiment. This verified that the FEA was accurate in its representation of the baler. While testing itself is not a formal design tool, the design of experiments is a considerable skill involved with design processes. The ability to understand, construct, and execute experiments to give proper results is important to analytical research.

5.2.12. Production Planning:

The Production Planning step of the design process, Figure 5.17, is the final step of the designers before delivery of the solution to the client. This process involves taking the geometry from the CAD step and formalizing it into presentable documents. This means that the geometry is laid out into professional 2D drawings that are properly dimensioned and labeled for manufacturing. The complete bill of materials is constructed so that the needed materials can be purchased. Additionally the vendor list is created so that the client does not need to search for a source for the materials.

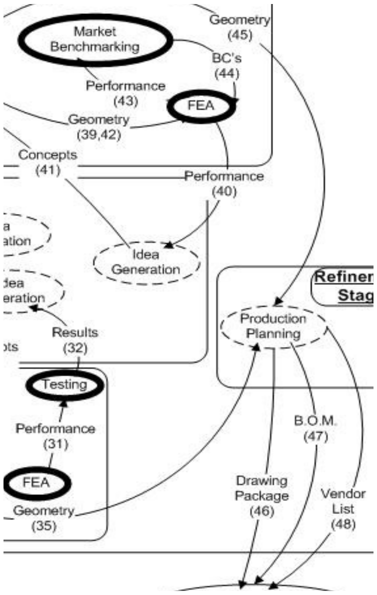


Figure 5.17: Production Planning Node

This step is completed by the designers utilizing design tools within the CAD packages to generate the 2D drawings. These are laid out so that a manufacturing facility can read and understand what is needed to build the design artifact. The formal design tools used in this step is the drawing package. The presentation and documentation of the other deliverables was done via software packages, but their use is not considered a formal design tool. The final delivery was complete when the designers gave the client the drawing package, bill of materials, and vendor list for the Baler and Structure construction.

5.2.13. Observations:

Six observations can be made from the DEIM representation of the EAI project. The observations that involve the DEIM representation include the following:

- DEIM construction iteration improves readability
- Existing labeling of DEIM does not support parallel node sequencing
- DEIM readability can benefit from using cognitive tendencies

An early version of the EAI DEIM below in Figure 5.18 shows the lack of downward and to the right propagation, a cognitive logic principle (Kim & Jang, 1999). By examining this map, the benefit of this theory to the DEIM can be seen in how easily the map is read. This early map is inspired by IDEF0's structure of nodes and links. However, IDEF0 restricts the ability to represent flow in a fluid manner because of the orthogonal and rectangular links. The size of nodes was also predefined, thus limiting the ability to lay out nodes clearly. This format also tended to confuse readers when establishing connectivity of specific nodes because of the links shaped at right angles. This was informally tested by having multiple readers not associated with the projects discuss the map. The findings proved that iterating DEIM construction improved the readability of the content.

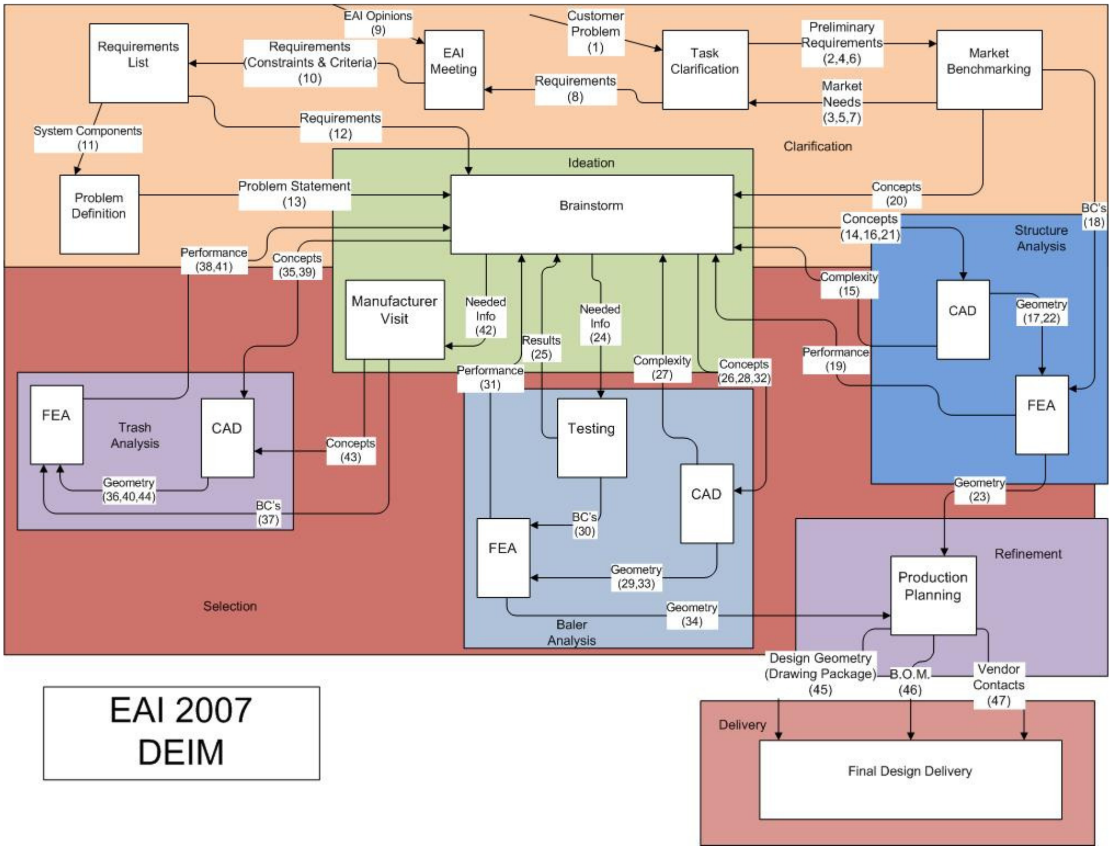


Figure 5.18: Early EAI DEIM

It can also be seen with this representation that exact sequencing is not possible with this representation and labeling form. While the precedence of each step can be determined, the exact order cannot. The numerical labels shown illustrate the general progression through the process, but not necessarily the order. For example, the Clarification stage uses numbers as sequence markers. At the first Idea Generation step, the process splits into three separate sub-processes, each occurring concurrently. The numbers then signify the sequence through any given stage of the process, but not the process as a whole. This limitation could be addressed with a modified labeling scheme, thus showing parallel events that occur such as (14, 27, and 36) becoming (14a, 14b, and 14c). Figure 5.19below illustrates such a parallel task situation.

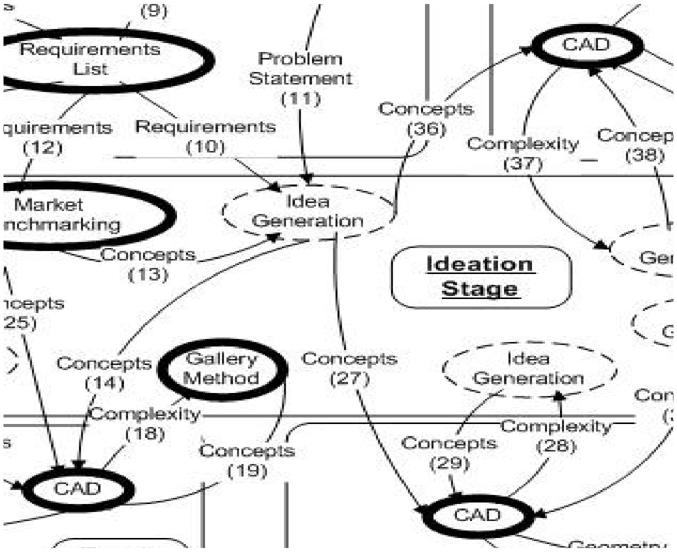


Figure 5.19: Sequencing Limitations with DEIM

The EAI DEIM also illustrates how map readability can benefit from cognitive tendencies. Traditional reading occurs from left to right and from top to bottom. Using this knowledge in laying out a DEIM can benefit the researcher with a much more readable map. By referring back to the early EAI DEIM in Figure 5.18 one can see that difficulty exists in locating the starting point and proper flow through the process. When compared to the existing DEIM in Figure 5.1, the benefit of using cognitive tendencies is revealed through the clarity of the refined map.

The observations that involve EAI concerning the case being represented include the following:

- DEIM construction iteration improves process content accuracy
- DEIM enables researchers to identify non-value adding nodes within a process
- DEIM enables researchers to identify information critical to a specific process

When creating DEIMs, iteration must also occur in order for the representation to accurately represent the process being modeled. Shown above in Figure 5.18 is the early iteration of the EAI map. Notice that some of the order of steps along with the content of the DEIM changed for the final map presented. Upon studying this early map, it was discovered that steps had been unintentionally omitted. By checking with designers that participated in the projects, additional firsthand experience was made available from a different perspective than that of the original process mapper. Post analysis of DEIMs gives the reader perspective to the process allowing a deeper cognitive relationship to be created when representing the process.

DEIM can allow the researcher to identify the critically needed steps within a process. By starting at the final design delivery, each subsequent step can highlighted. This can propagate all the way up to the initial customer input. By doing this, connection of each part of the DEIM to the final design delivery can be determined. In doing so, non-value adding steps are identified, revealing to researchers the wasteful steps within the process.

By studying the following maps, Figure 5.20-Figure 5.23, it can be seen that the Trash Analysis Stage along with Idea Generation Steps connected to it produced no work that contributed to the final design. This occurred because the effort required to model compacted trash behavior is extensive and the client decided to purchase an existing unit rather than consume resources to develop a new one. The identification of non-value adding nodes begins in Figure 5.20, with the final product. The required input information to that node is identified and then the source nodes of that information are then highlighted. This process propagates back through the process until the initial step is reached. Once a complete path of value adding nodes reaches from the final solution to the initial link, the process evaluation is complete. At this point, any remaining nodes are non-value adding.

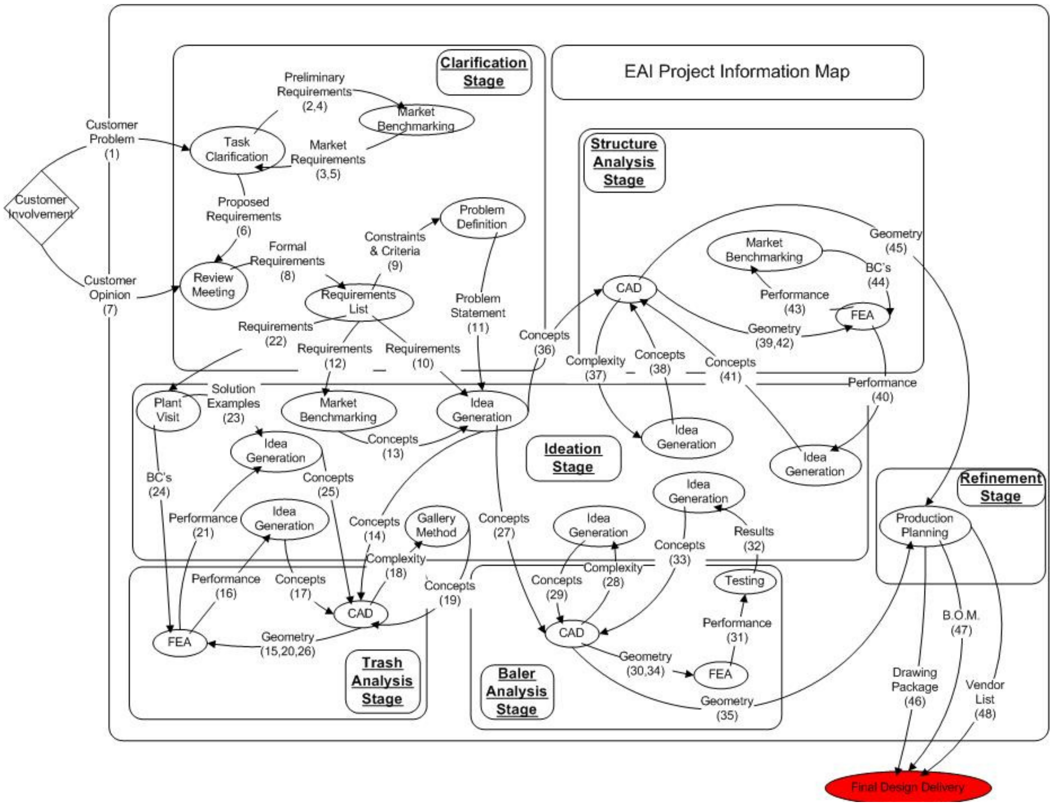


Figure 5.20: Back Propagation Step 1

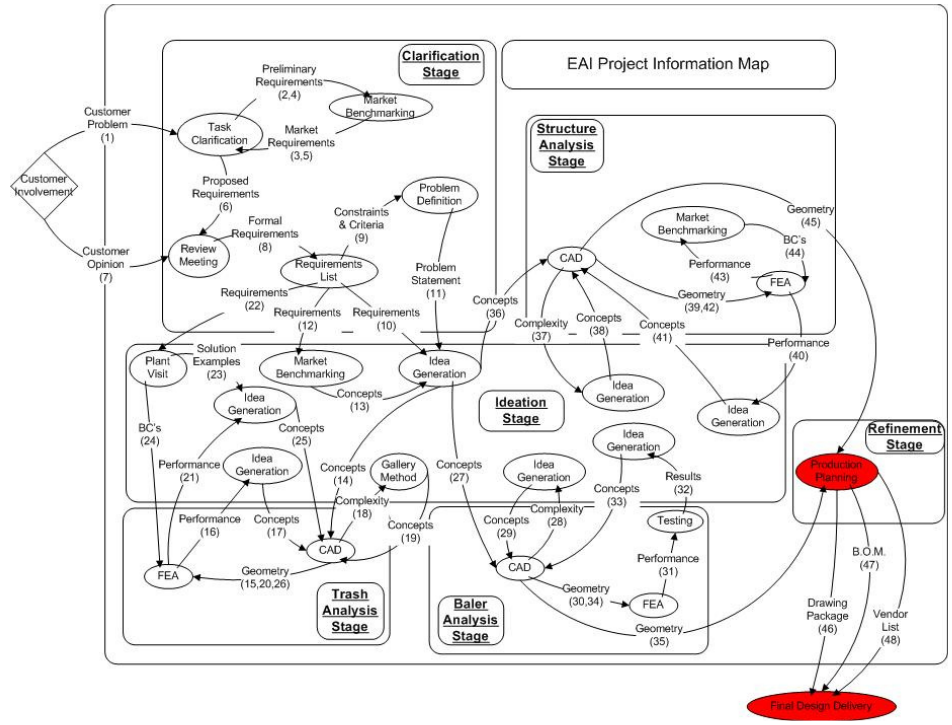


Figure 5.21: Back Propagation Step 2

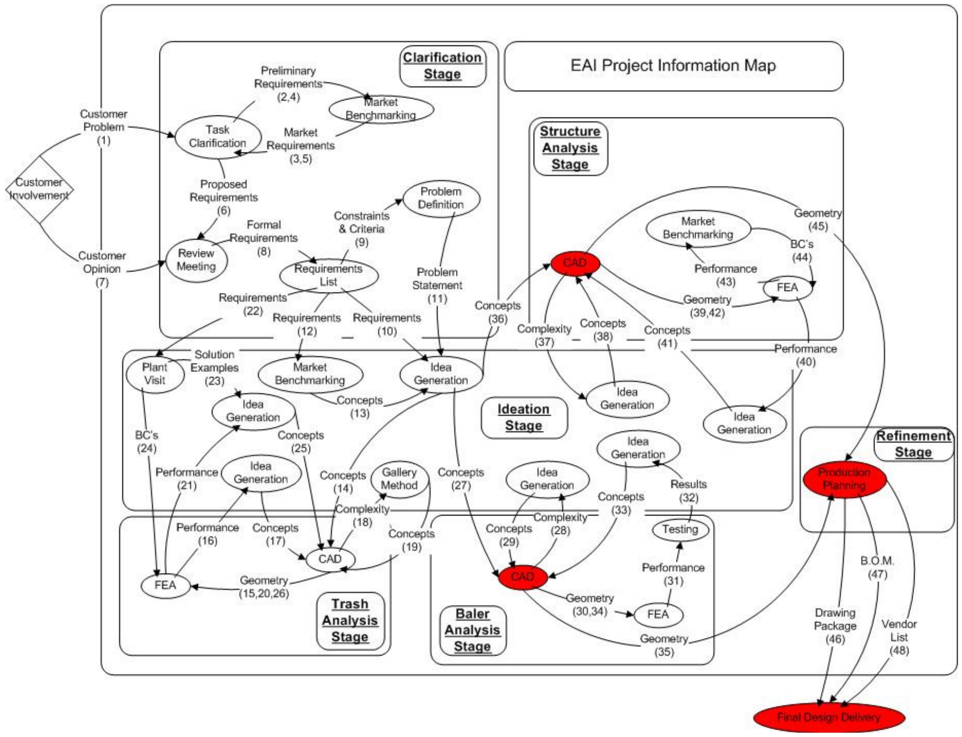


Figure 5.22: Back Propagation Step 3

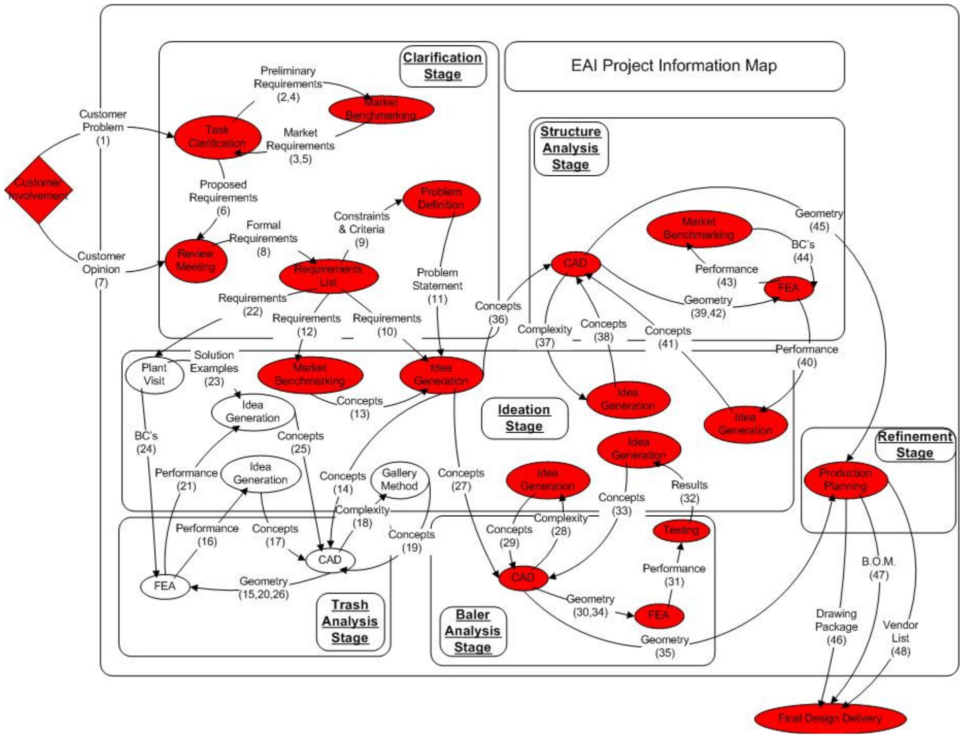


Figure 5.23: Back Propagation Complete

By reading the DEIM, it can be observed what specific information is needed to complete any given task or achieve a desired information entity. For example, in the top right corner a Market Benchmark step exists. To complete this task, the *performance* results from the FEA step are required. When the designer has these results, and completes the Market Benchmark step, *boundary conditions* will be generated and used to repeat the FEA step. This is shown below in Figure 5.24

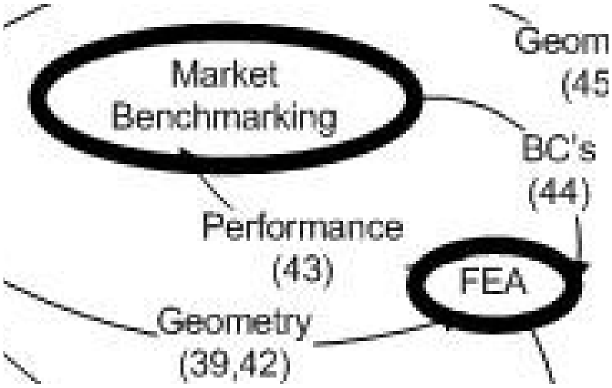


Figure 5.24: Market Benchmarking Input and Delivered Information

5.3. The WMP Project

The Wright Metal Products (WMP) project was a four month long, sponsored design project. The client purchased a welding robot, and wanted the designers to develop an efficient work area to use the robot in their facility. The client manufactures steel shipping crates out of pre-cut parts which are then welded manually in the facility. The goal of this project was to improve efficiency and production by using the robot along with manual workers. The client gave freedom to the designers to specify all needed layout, equipment, and fixtures that would be needed. The DEIM for the WMP project is shown below in Figure 5.25.

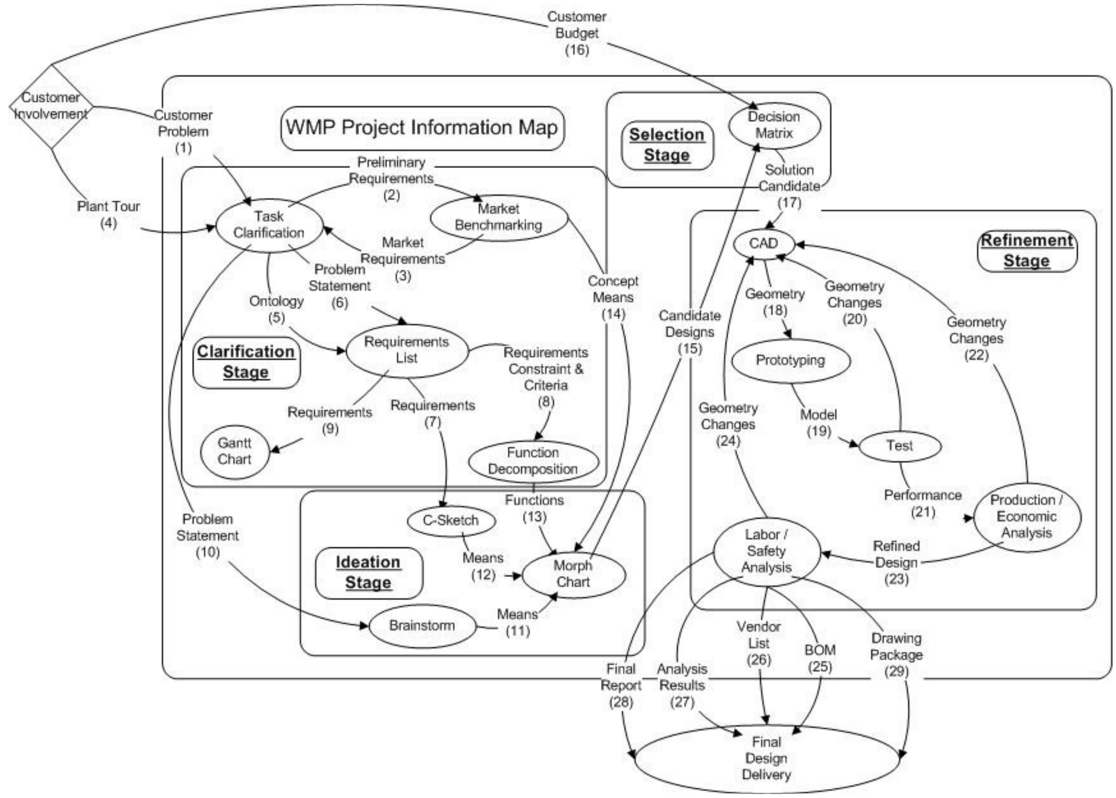


Figure 5.25: WMP DEIM

It can be seen that this map does not contain the bold, thin, and dotted node outlines. That representation scheme was used in the EAI map to differentiate the different classifications of nodes that were used. For the WMP map, most of the nodes were formal design tools, therefore adding the different node formats would only serve to add information to the map which is not desired. For comparison, the WMP map is shown below in Figure 5.26 with the nodes highlighted according to formality, similar to the EAI DEIM. Notice that the benefit of node shading for this particular map adds little value of information. It does, however add non-uniformity to the DEIM which limits the clarity of the map.

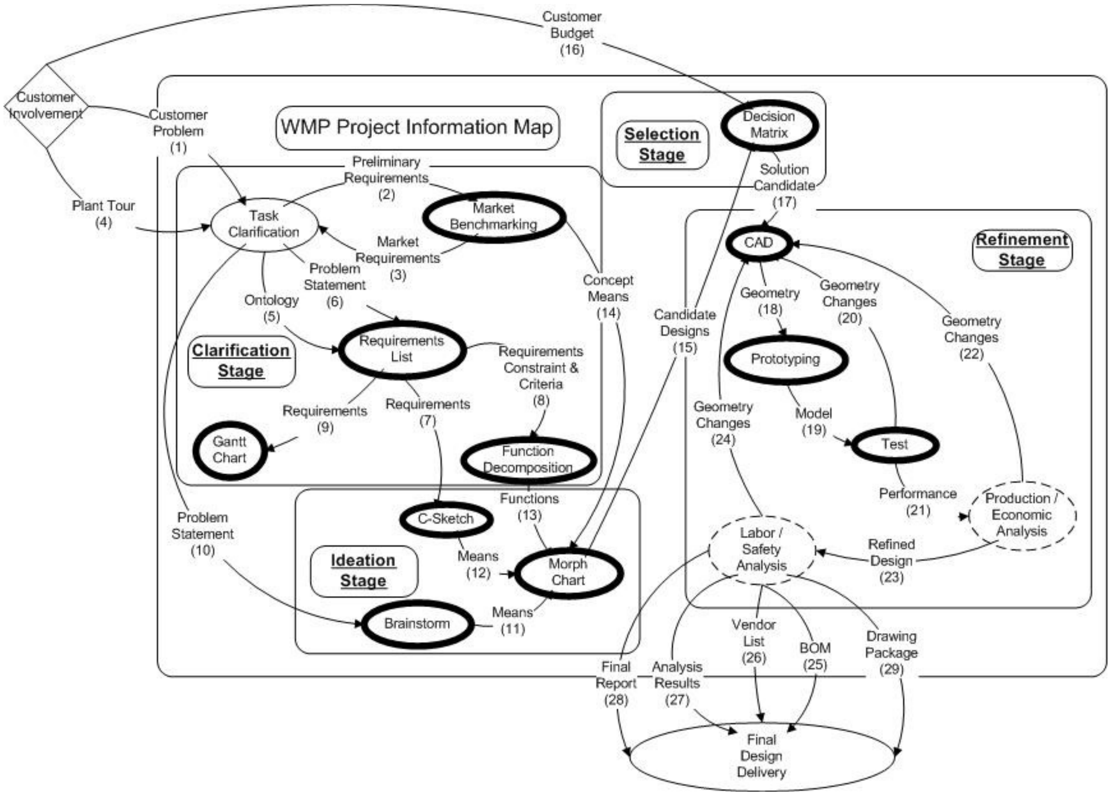


Figure 5.26: WMP DEIM with Node Line styles

The WMP design process began with the client addressing the designers. The *customer problem* was given to start the design process. The designer then began refining the *requirements* of the process by benchmarking market examples of welding robot layouts. This step served to give the designers a deeper knowledge of the *requirements* that such a work cell needed to accomplish. The Ideation Stage of this design process consisted of a Brainstorming session, a C-Sketch session, and a Function Decomposition session. Each of these was used to populate a Morphological Chart with means for the appropriate *functions*. Then *candidate solution* concepts were entered into a Decision Matrix. The factors needed to make a selection were established in discussions held with the *client*.

Once the best *candidate designs* were selected, work began to generate CAD models of the solution. At this point in the design process the analytical iterations began. CAD models were used to build Prototypes. The resulting Prototype was then used to suggest changes to the design, which then changed the CAD models. This proceeded into the Testing step, where an appropriate Prototype was used to test the functionality of the design. The results of the test were then used to modify the CAD models again, and the process continued until test results were satisfactory to the designers.

When the design functioned suitably for the designers, it was analyzed for economic and production demand. If the design candidate had components with costs too high, or the production limit with the design was too low, then changes were made, and new CAD models were then built, tested, and validated. This repeated until sufficient cost was reached and the production limit with the design was satisfactory. The last analysis completed on the proposed design was of the laborer demand and safety. This *requirement* was paramount, and thus used as a final filter eliminating any exhaustive or dangerous design candidates from those proposed to the client. When the labor and safety analysis was completed, the designers then formalized all of the information into professional documents that could be presented to the client. The *drawing package* for the proposed design, the *bill of materials*, the *vendor list*, the *analysis results,* and the *final report* were all delivered to the client.

This project consisted of four main stages, starting with the Clarification, proceeding to the Ideation, then to the Selection, and completing the process with the

Analysis. The Clarification stage served to properly define the problem and develop forma Requirements that must be met by the solution. The Ideation stage encompassed three idea generation techniques and the formation of a Morphological Chart to aid in concept organization. The Selection stage was the shortest in duration and consisted of the use of a Decision Matrix to rank solution candidates allowing the designers to choose the better concepts from all the ones generated. The final stage was the Analysis stage, where the solution was tested, analyzed, refined and validated into a suitable solution.

5.3.1. Observations:

Two observations can be made about the DEIM representation of the WMP project. These include the following:

- DEIM is flexible with respect to node classification and formality
- DEIM is flexible with respect to node grouping

In the WMP project, more specific design tools and methods were used than appeared in the EAI DEIM. The nodes of this map serve as precise design methods or tools. Some may be formal such as the use of Morphological Charts, while others can exist in a more general context like the labor and safety analysis. Typically, the flexible nodes seemed to require the most effort and time to complete, due to the ambiguity of the task, although time is not shown in the WMP DEIM. A C-Sketch session could be completed in a single design meeting but the economic analysis required weeks to collect the appropriate data so that the needed measurements of the design solution could be taken.

The grouping of nodes in a map is at the discretion of the mapper. If design stages group nodes then the map can show that. However, if other means of grouping should be desired, this is also possible. Additionally, grouping boundaries can be stacked, meaning that a specific set of nodes occurs entirely within another set, but does not comprise that set entirely. An example of design stage boundaries is shown in Figure 5.27.

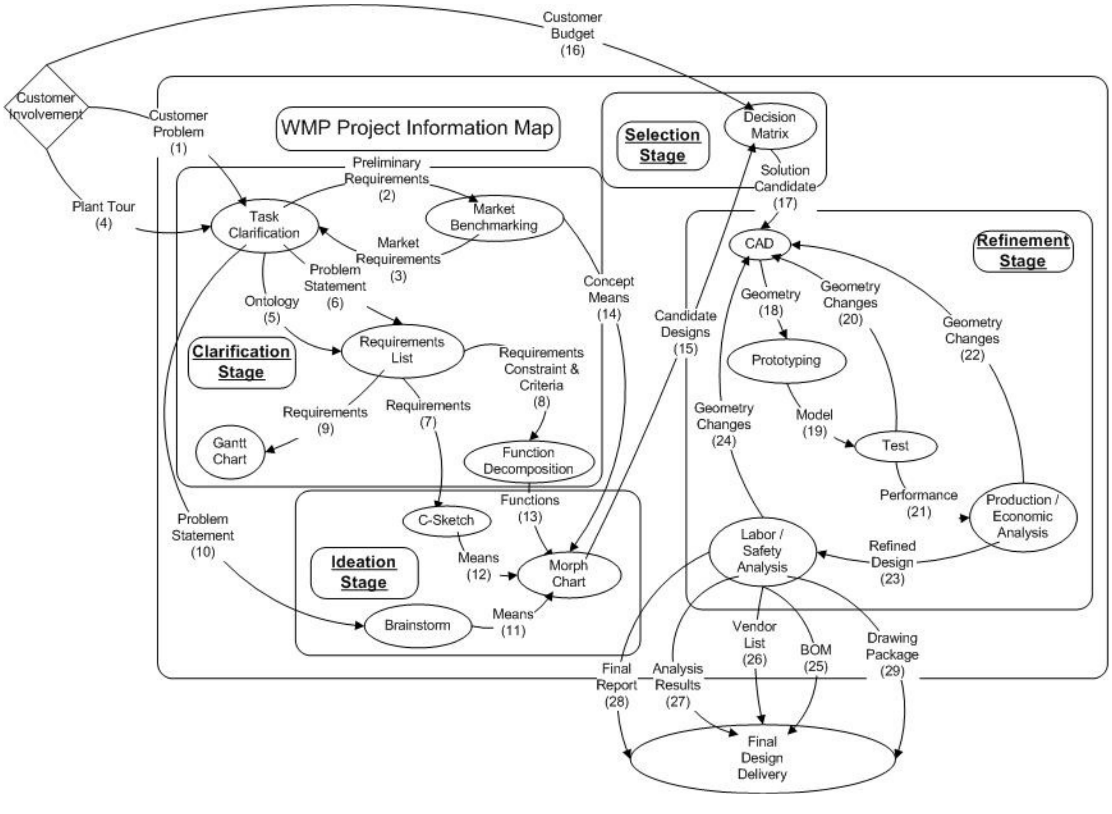


Figure 5.27: Design Stage Boundaries

Two observations can also be made about the WMP case through the application of DEIM. These include:

- DEIM can enable researchers to identify non-value adding nodes
- Nodes can alter information and channel information

Similarly to the EAI DEIM, this map can allow researchers to back propagate through the process and identify non-value adding steps. Once the establishment of each node as value adding reaches the initial stage, then the propagation stops and any remaining nodes are non-value adding.

Some of the nodes in the WMP map accomplish dual functions. The first is that the node functions as the modifier of the information. Initially, this feeds back into the previous steps for iteration. However, when the information again reaches the same node, a different "check" may occur, thus allowing the information to "pass" through the node on to the next. An example of this occurrence is shown below in Figure 5.28.

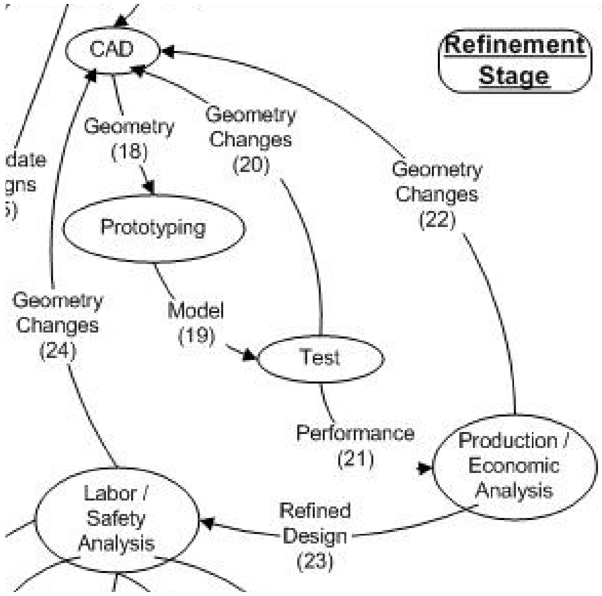


Figure 5.28: Dual Function Nodes

5.4. The Michelin Project

The Michelin project was a 12 month long project that began when representatives from Michelin Tire Co. approached the engineers with the topic of test procedure development. They were interested in understanding a soil and tire interaction and wanted to investigate the possibility of the designers developing an economic solution to their need of testing. The DEIM of the Michelin Project is shown below in Figure 5.29.

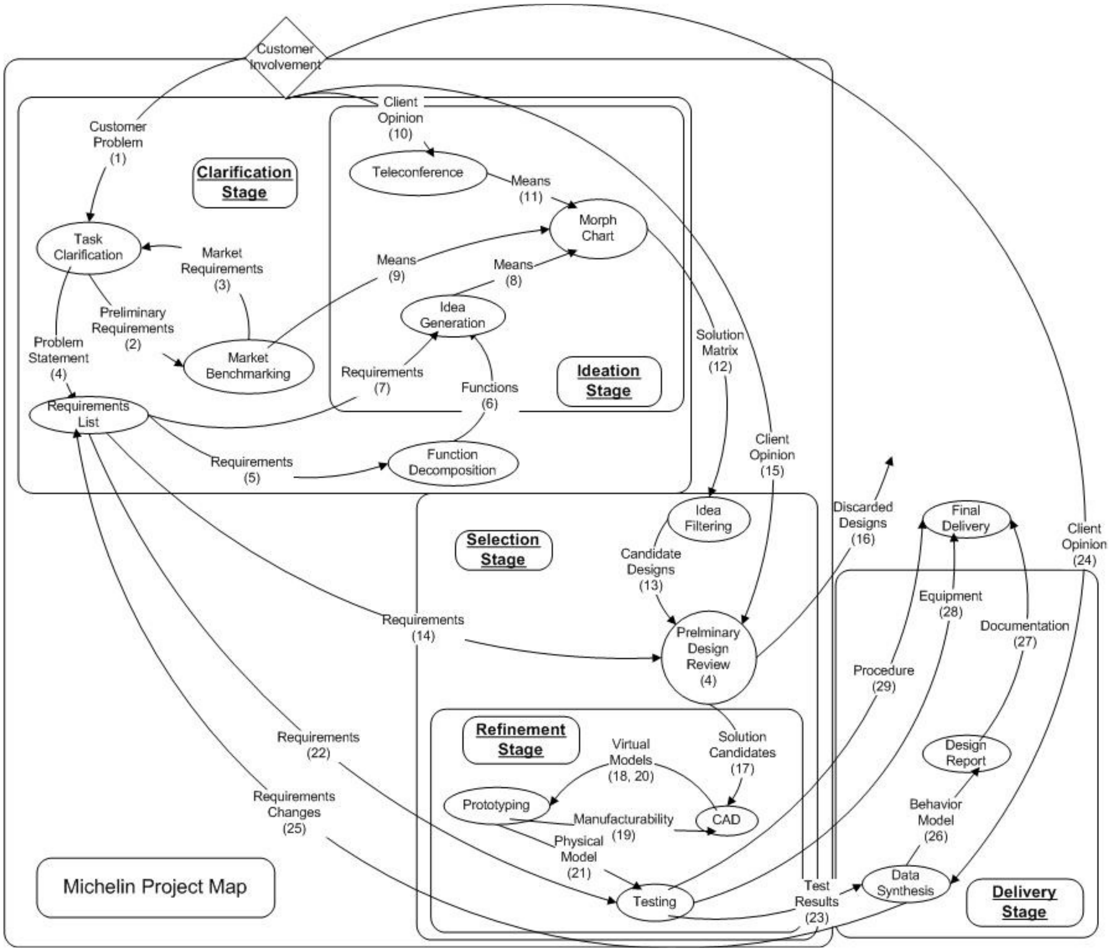


Figure 5.29: Michelin DEIM

Tires are a complex machine, and the construction and simulation of their behavior is not a simple task. To test specific behaviors, tires are generally constructed, and used to examine the performance of certain parameters. The engineers will then specify changes, and will need to manufacture a new set of tires. This is costly due to tire mold manufacturing cost. The testing cost limits the ability of the tire engineers to learn about the behaviors, so the need of a simulation protocol with more economic operational cost is warranted. This was the goal of the designers, as specified by the customer.

This project was greatly different from the other two case studies used in this Thesis. Unlike the others, this project example was meant to produce behavioral testing equipment and procedures that would allow the client to relate test results to real world behavior in an economic manner. While some physical artifacts were delivered, the main deliverable is the set of test equipment along with the protocol of testing that will allow proper understanding of the phenomenon.

Work started by early research being done to further understand the behavior of tires in soil. Preliminary tests were done with existing tires and publications were reviewed to try and give context to some of the problems being addressed. Ultimately a formal *problem statement* was generated and approved. From this, the *requirements* needed were listed and work was done to decompose the problem into its fundamental issues. Various idea generation methods were used to form solutions to the elemental problems at hand, and were combined using a Morphological Chart into solution concepts. Each of these concepts was then evaluated according to *client opinions* and the *requirements* of the project. The *solution candidates* were then developed into CAD models. These models were evaluated for feasibility via Prototyping which was used to refine the CAD models based on manufacturability.

At this point in the project, the progress of the designers slowed significantly. Once a manufacture-able design was developed and built, testing proceeded. The testing step showed the ability of the testing equipment to accurately represent real world conditions. The results of the tests were synthesized into readable information and analyzed for conditional comparison. The generated representations were not sufficient to the client, who then stated that some of the *requirements* had not been met. After discussion, the *requirements* were modified and additional equipment and procedures were designed and developed in a manner similar to the first iteration. The *behavior model* of the tires was used to form design reports that served as justification for the decisions made. Once this was complete, the delivery of the equipment, training the tire engineers on the testing procedure, and supplying the client with the Design Report containing the analysis and design justification was all that remained.

Specific events slowed the production and completion of this design project. Sufficient *requirements* were not established when the Requirements List was initially formed. The project continued, and suitable design solutions were formed, but the client required features that were not part of the initial Requirements List. This meant that the Requirements List had to be refined and the design process repeated with the new Requirements List. This repetition is shown in Figure 5.29.

This iteration spans almost all of the steps in the project. Because of this, the completion of the project took much longer than predicted. Pahl and Beitz call such iterations, iterating late and rarely but suggest iterating design processes often and early in order to avoid lengthy repetitive stages, like those encountered by the Michelin Project (Pahl & Beitz, 1995).

5.4.1. Observations:

Six observations can be made from the DEIM representation of the Michelin project. Those concerning the representation used include the following:

- DEIM can show non-critical information if the mapper wishes
- DEIM is flexible with respect to node grouping

DEIM has the ability to leave out or include information links of concern. The *discarded designs* shown in Figure 5.30 exit the design process and are not used. These did not need to be shown in order to accurately represent the design process. However, by showing them, the reader can mentally retain that other design solutions existed and were discarded. The reader can also relate those designs to a specific tool within the design process, the Preliminary Design Review. If documents were created that contained information about those designs, they could be investigated for further analysis. The ability to show wasted information allows the researcher to back track the work done and possibly modify the process for future iterations, with a modified process eliminating solutions contained in the wasted link. This increases the efficiency of future iterations of the process, and helps avoid lengthy process repetitions.

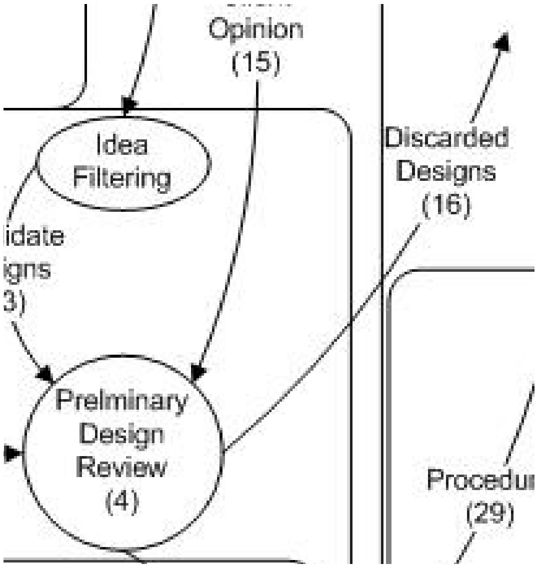


Figure 5.30: Illustrated Discarded Designs

Like the WMP map, the Michelin project also has various forms of node grouping boundaries. This particular map, in Figure 5.31, illustrates an example of stacked boundaries, meaning that the Refinement Stage is part of the Selection Stage, but not all of it.

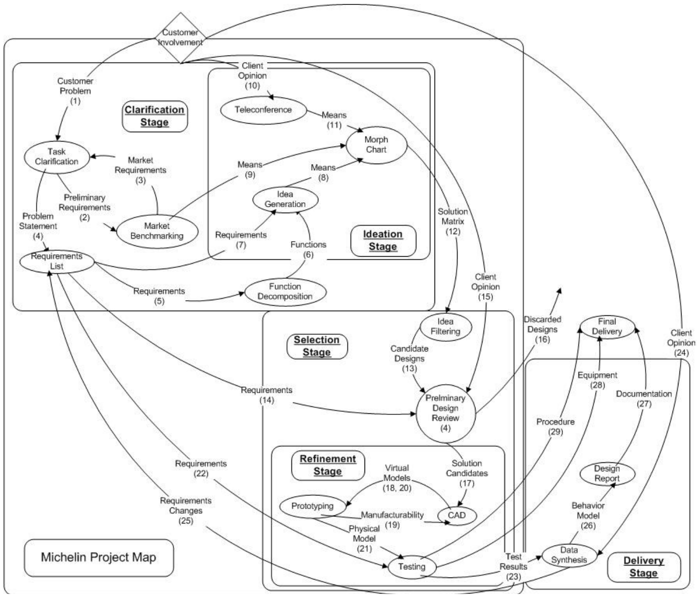


Figure 5.31: DEIM Boundary Stacking

The observations that can be made from the WMP DEIM concerning the case itself are:

- Link length may be proportional to specific information properties
- Node connectivity may be proportional to specific information properties
- DEIM can show the result of insufficient information
- DEIM can show the effect of making long iterations

It can be seen with this map that the length of the links is proportional to the goodness of the design process. As mentioned above, early and often iterations make for better design processes, whereas the links representing those iterations would be spaced close together and in stages rather than in long sweeping curves as shown in Figure 5.32. The link length in this DEIM varies greatly from node to node. This communicates some information about the process such as time required to iterate and percentage of time wasted by the iteration.

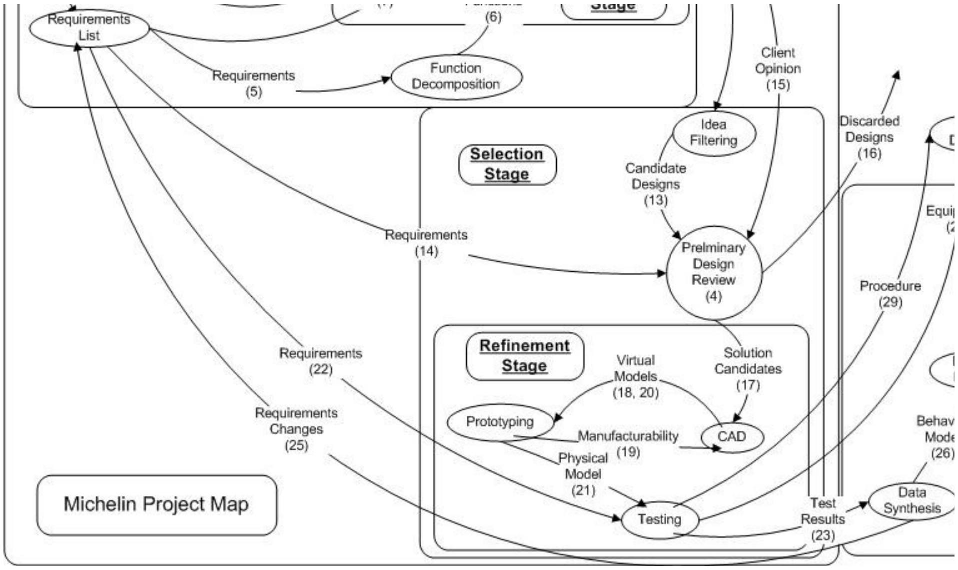


Figure 5.32: Process Iteration Links

The Michelin DEIM shows relationships of node connectivity to the difficulty of that part of the process. If a node is highly connected such as the Requirements List or the Customer Involvement, then accurate and precise information from that source is needed for the design process to proceed properly. Accordingly, incomplete or inaccurate information from highly connected sources works against the productivity of the design process. As mentioned above, the lack of exhaustive *requirements* by the customer hindered the progress of the design project. If the significance of the Requirements List been known initially, the designers may have urged further clarification and development of the Requirements List before proceeding on to the next step of the design process.

The Michelin DEIM also shows the effect of insufficient information being used in a process. Fault of this deficiency cannot be given, but the effect of completing most of the process without it can be shown with the map. As the design data is being synthesized, discoveries were made that amended the *requirements* of the process. DEIM shows this by connecting a late node to an early node, thus initiating an almost complete process repetition.

Similarly, the effect of that long iteration from the lack of *requirements* can be seen. By making the connection back to the Requirements List, the exact number of nodes, and therefore work, can be counted that will be needed to complete the process. Additionally, the redundant or wasted effort, time, and resources can be estimated to determine the inefficiency of that particular process.

Chapter 6

CONCLUSIONS

6.1. Thesis Summary

This thesis has provides three case studies in which the design process has been represented graphically using the design tools and information contained herein as the building blocks of the design process. The information initiating, flowing through, and exiting these design tools has been used to connect different tool nodes in an information map. The qualities of the information contained in these maps are defined by the user, thus allowing a flexible design process representation that is constructed within the context needed by the researcher studying the map. By studying these maps, the benefit of this work to the design community is beginning to be understood.

By representing information within design processes, researchers can model complex processes graphically. Doing so gives researchers a better mental connection between what is perceived and what is real. With better understanding comes improved ability to analyze design processes with case studies. This enhanced understanding also contributes to the design research community by enabling behavioral models which may someday give control of the design process to the designer. These improvements were shown through the application of a newly developed design process model in three case studies. Each case consisted of different deliverables, different experience levels of the designers, and project durations. The use of case studies to develop design tools and conduct design research has been proved beneficial by the successful application of and evaluation with DEIM to the case studies.

6.2. DEIM Observations

Through conducting these case studies, observations about the DEIM representation of design processes can be made and are:

- DEIM construction iteration improves readability
- Existing labeling of DEIM does not support parallel node sequencing
- DEIM readability can benefit from using cognitive tendencies
- DEIM is flexible with respect to node classification and formality
- DEIM is flexible with respect to node grouping
- DEIM can show non-critical information if mapper wishes
- DEIM is flexible with respect to node grouping

These observations illustrate ways that researchers can benefit from a graphic representation of design processes and that design processes can accurately be represented graphically while containing sufficient detail and promoting readability.

Observations about the cases studied through the application of DEIM were also made in this Thesis and are:

- DEIM construction iteration improves process content accuracy
- DEIM enables researchers to identify information critical to a specific process
- DEIM can enable researchers to identify non-value adding nodes
- Nodes can alter information and channel information
- Link length may be proportional to specific information properties
- Node connectivity may be proportional to specific information properties
- DEIM can show the result of insufficient information
- DEIM can show the effect of making long iterations

DEIM allows a predefined view of the process to be defined. This can be shown graphically via boundary lines and collecting tasks into stages or other classifications of groups. This gives DEIM readers the ability to see entities that actually exist within the process scope and those that do not. It also allows the reader to determine the source of information entering a node, be it from an adjacent node, or a source exterior to the process scope.

Information paths can be easily traced with DEIM. From the initial problem of the client to the documentation or artifacts that are physically delivered to the client, the type, quantity, and change of the information present at any given stage of the process can be displayed. This gives designers an ability to determine "Next Steps" for each process as well as determining information that may be needed to complete a specific task.

The affect of a specified node on another can be determined with DEIM as well. To find the affect of altering a specific task, the researcher can follow the propagation of information through the process to determine what subsequent nodes will be changed. Additionally, hierarchies of design tasks, or any entity represented by nodes, can be formed easily by reading DEIM and forming the relationship architecture from the content of the map.

The critical path of information flow can be determined from reading DEIM. This can be done via back tracking the preceding nodes or any other means desired. The representation of links and nodes allows a holistic understanding of the process to advance into a detailed understanding of information that enters and exits any specific node.

DEIM allows the mapper to specify how information links and nodes are grouped. The examples shown are primarily grouped according to Stage of Design Process. However, the EAI DEIM shows analysis stages that are grouped according to sub-system context. Mappers are able to group any and all information into the context that suits the researcher. This enables DEIM to be used for many different applications of process study, and in many different areas of concern.

The ability to discover alternate means of accomplishing a task is valuable to designers. DEIM enables the researcher to see node options based on the outcome of the task being modeled. This gives the researcher the ability to specify the known information and select the next appropriate action from a list of nodes which will allow the information link to transform into what the designer wishes. DEIM uses process redundancy in allowing the designer to generate the same information with multiple sup-process tasks. This can be useful in comparing tools and their efficiency.

DEIM is a flexible representation of the information that the designers is involved with. As shown in the Michelin case, wasted information can be represented in the maps. Other domains of information can be compounded into the same maps, allowing the researcher to examine many different aspects of the process on one image. DEIM can show information used, information discarded, resources used, task responsibilities, and many other domains which can be used to describe a process. The main benefit is that what is shown is at the discretion of the mapper. If a specific case generates waste and the relationship of that wasted information is important it can be shown. However, if the effects of that waste are of no concern to the researcher, it can be omitted from the map without penalty as proved with the case studies.

The connectivity of the nodes within a DEIM can also be seen. It was shown that DEIM nodes that are highly connected tended to be significant contributors to the design process. The concept of this metric can be used to build DEIM in respect to other characteristics such as production dependencies, or information management. In the case studies shown, the connectivity relates to both the affect that the particular node has on other nodes as well as the difficulty that can be encountered when constructing DEIM containing that specific node.

More importantly, the development, application, and evaluation of new design tools and methods through the use of case studies has been proven. The three cases used show the benefit of the developed representation through the information revealed about the cases. The cases served to test the new representation, and allow the author to discover information about the representation that was previously unknown. These observations have been mentioned in the previous section. Furthermore, the application of the new tool to case studies has also shown that case studies can be used to evaluate design processes, in attempt to understand the process meaning that future endeavors of modifying and improving the process are possible.

6.3. DEIM Limitations

Certain limitations were encountered when using DEIM to represent tools used in processes. These difficulties came from constructing the DEIM as well as reading and understanding the process being represented. The first difficulty is the difficulty to search for specified objects (links or nodes). With other representations such as DSM, readers can search for a specified entity in a one dimensional, linear manner by scanning either a column or row heading. DEIM expands the representation into a full two dimensional space, thus making searching more difficult. This was addressed by Keller et al as well in their Matrix vs. Node Link evaluation (Keller, Eckert, & Clarkson, 2006).

The layout of the nodes is also a cumbersome and tedious process. Simple and somewhat linear process can be represented fairly quickly by simply connecting links and nodes progressively until the process is complete. However, for highly complex processes, layout of nodes on the map is critical to proper clarity. It is difficult to position the nodes of highly connected processes in a manner such that the links do not intersect. In fact, sacrifices must sometimes be made when constructing the maps to show some information and alter others. The Michelin map was a highly connected process with specific nodes posing great difficulty in positioning for accurate representation. The Requirements List as well as the Client Information nodes often wanted to intersect. The sacrifice of link length was made to show proper connectivity. DIEM is a user defined representation of the process. It could be beneficial to allow link intersection sometimes, thus creating another entity which can represent additional information about the process. However, this is at the discretion of the mapper.

Similarly, the representation of any information property within DEIM requires planning and thought. The maps developed show few properties of the information available. The maps shown represent connection and progression of the information throughout the process. Other qualities of the information can be represented, but how they are represented and organized in the map must be established first. For example: the number of designers in a project task may be of interest to the DEIM researcher. This could be shown with a feature such as node size. For a task which consisted of eight designers, the size would be eight, but a later task may only use three designers, therefore the size of that node would be three. Naturally, by representing such information, the ability to represent others is hindered. Relating link length to some characteristic would be difficult after specifying size restraints for the nodes. When constructing a DEIM, having ontology of the information and tools used in the map would benefit the researcher. Such information would enable proper context to be given to each item used in the DEIM as well as control the terminology used to describe the links and tools used.

Finally, the construction of a DEIM representation of design processes requires iteration. This is not to say that the process is not well known, but dissecting the understanding of the process sometimes takes repetition. By building a DEIM the mapper creates a first attempt of representing the information. Some information in the map will be accurate while others will be incorrect. Still others will require further detail to properly model as the researcher needs. Exposing the benefit of iteration is best done by a colleague of the mapper who did not construct the first version. Allowing multiple readers to evaluate and critique the map that are familiar with the process being modeled will greatly increase the value and accuracy of the information represented. It is recommended that initial construction of DEIM be completed by a single mapper. Consulting a colleague can then stimulate further detail and accuracy in the map without blocking the creative concentration of the mapper.

6.4. Future Work

The work presented in this thesis leads to some areas of future investigation. Many issues discovered and addressed in this thesis pose qualifying arguments which warrant further work for better understanding. Suggested research topics are given.

The first area of future work is the exploration of domain representation methods. They ways in which information domains can be shown within a map cannot currently be counted. Future work could include ways to determine how many different ways information can be represented. Additionally, methods of identifying those representations should also be developed as well as establishing what types of information that can be shown. An appropriate research topic for this is; "Developing an ontology of design tools and information and the grammar that connects them."

The ability of DEIM to illustrate the sequence of operations within a design process is also of value to researchers. Future work could be focused on how to represent time and process sequence within the DEIM. Proper selection of a representation scheme for time as well as the organization needed to accurately show sequence within the map should be investigated. An appropriate research topic is; "How should sequencing and temporal stamping be represented?"

DEIM contains complexity that could greatly benefit from computer integration. Implementing the theory presented in this thesis into a software package could prove to generate a useful and powerful tool for designers. Design disciplines such as project management could use such a program in researching and developing their own principles. The visual representation of the existence of design documents is a valuable contribution of this work. However, taking this work further should include database structures which will "hyperlink" each node to the specific file that is stored. Similarly, computer implementation could allow the layout of DEIM to be selected automatically, based on some layout optimization algorithm. The theory and steps to DEIM construction could also be programmed giving a more error proof construction of the maps. Finally, extension to other process models can be made, thereby increasing the usability of not just DEIM but of a multitude of other tools as well. Creating a program that is compatible with Microsoft's Project could automatically generate PERT diagrams and Gantt charts from the same work done in DEIM. A suitable research topic would be, "Implementing automation principles to expand design tool function and usability".

More case studies should also be completed using DEIM to model the processes. These case studies give specific context to issues revealed in each map and allow researchers to relate the fundamental elements of DEIM to the details of design processes. In particular, case studies to identify dead ends in processes could yield benefit to the improvement of the process itself. The exploration of an appropriate sample size of cases as well as the investigation of observations made herein could greatly expand the work done by this thesis. An appropriate research topic is, "Exploring case study observations and expanding them to an experimental level".

The theory of information mapping reveals issues that could prove beneficial to process representation schemes. IDEF0 is a successful scheme which focuses on the function as well as things that enter and exit it. DEIM works in a similar manner. The application of the Conservation of Energy principle into information mapping could prove beneficial. By using theory stating that "information cannot be created nor destroyed, but can only change form", researchers may be able to enhance the way that design processes are understood and completed. Similar benefit may also be had by investigating the integration of Boolean Logic into information maps. An appropriate research topic is, "Applying the theory of the Conservation of Energy to information mapping within design processes".

By identifying non-value adding steps, DEIM opens opportunity of integration with lean manufacturing process models. This can also be an extension of a software package. By exploring the theory of both lean manufacturing and DEIM, researcher may be able to discover similarities, thus enabling the design community to gain a broader and applicable model to understanding processes. An appropriate research topic for this is, "Applying lean manufacturing principles to design process models".

Finally, the expansion of design process models away from verbal descriptions into visually grounded renderings should be continued. This thesis has formed two dimensional representations of complex and real world design processes. Upon examining those maps, certain difficulties were identified and some were understood. By continuing the research started by this thesis, the design research community can be populated with a tool that can organize design process information, display it in a clear and concise manner, and allow the process to be manipulated to change characteristics at the researcher's discretion. A lofty future goal of this research is to enable designers to use complex and detailed scientific visualization tools similar to CAD software packages to represent design processes in a multi-dimensional virtual environment. This would give greater capability and freedom in information mapping and process modification to the researcher by representing design processes in virtual three dimensional spaces. A suitable research topic for this is, "Developing a multi-dimensional virtual representation of design processes".

APPENDICES

Appendix A

Generic Tool Matrix		Outcome																													
		Requirements											Ideas						Analysis						Deliverables			Examnination			
	Inputs	Customer Problem	Preliminary Requirements	Market Requirements	Proposed Requirements	Customer Opinion	Formal Requirements	Constraints and Criteria	Requirements	Requirement Weights	Problem Statement	Boundary Conditions	Candidate Concepts	Selected Concepts	Feasibility	Solution Examples	Functional Means	Functions	Geometry	Components	Performance	Complexity	Revisions	Results	Drawing Package	BOM	Vendor List	Process Performance	Model	# of Tools	# of Products
Requirements	Customer Problem	1	Task Clarification		Task Clarification																									1	2
	Preliminary Requirements		1	Market Benchmark																										1	1
	Market Requirements		Task Clarification	1	Task Clarification																									1	2
	Proposed Requirements				1		Review Meeting																							1	1
	Customer Opinion				Review Meeting	1	Review Meeting	QFD		QFD Kano Analysis																				3	4
	Formal Requirements						1	Requirements List QFD	Requirements List	QFD																				2	3
	Constraints and Criteria							1			Problem Definition			Decision Matrix																2	2
	Requirements								1	Kano Analysis		Plant Visit	Idea Gallery Market TRIZ Sketching Prototyping FMI Brainstorm	Plant Visit Decision Matrix	Checklist DFM Compatability Analysis			Function Decomp FMI			Prototyping DFM	DFM	FTA Fishbone Diagram					Checklist		17	9
	Requirement Weights									1				Decision Matrix																1	1
	Problem Statement										1		Idea Brainstorm TRIZ Sketching Gallery Method																	5	1
	Boundary Conditions											1									FEA									1	1
Ideas	Candidate Concepts												1	Decision Matrix	Compatability Analysis DFM		Morphological Chart				DFM	DFM								4	5
	Selected Concepts													1					CAD	CAD		CAD								1	3
	Feasibility														1															0	0
	Solution Examples												Idea Generation			1														1	1
	Functional Means												Morphological Chart				1													1	1
	Functions												Morphological Chart Prototyping		Compatability Analysis			1			Prototyping		FMEA FTA Fishbone							[illegible]	4
Analysis	Geometry													FEA	DFM				1		FEA DFM	DFM			Production Planning	Production Planning	Production Planning			3	7
	Components												Prototyping		Compatability Analysis DFM			Function Decomp		1	Prototyping DFM	DFM	FMEA FTA Fishbone							7	7
	Performance							QFD	Market Benchmark	QFD		Market Benchmark	Idea Generation Market Benchmark								1		FTA Fishbone Diagram	Test						[illegible]	7
	Complexity												Gallery Method Idea Generation									1								2	1
	Revisions																						1							0	0
	Results												Idea Generation											1						1	1
Deliverables	Drawing Package														DFM							DFM			1					1	2
	BOM																									1				0	0
	Vendor List																										1			0	0
Examnination	Process Performance																											1		0	0
	Model													Reverse Engineering				Reverse Engineering		Reverse Engineering		Reverse Engineering							1	1	4

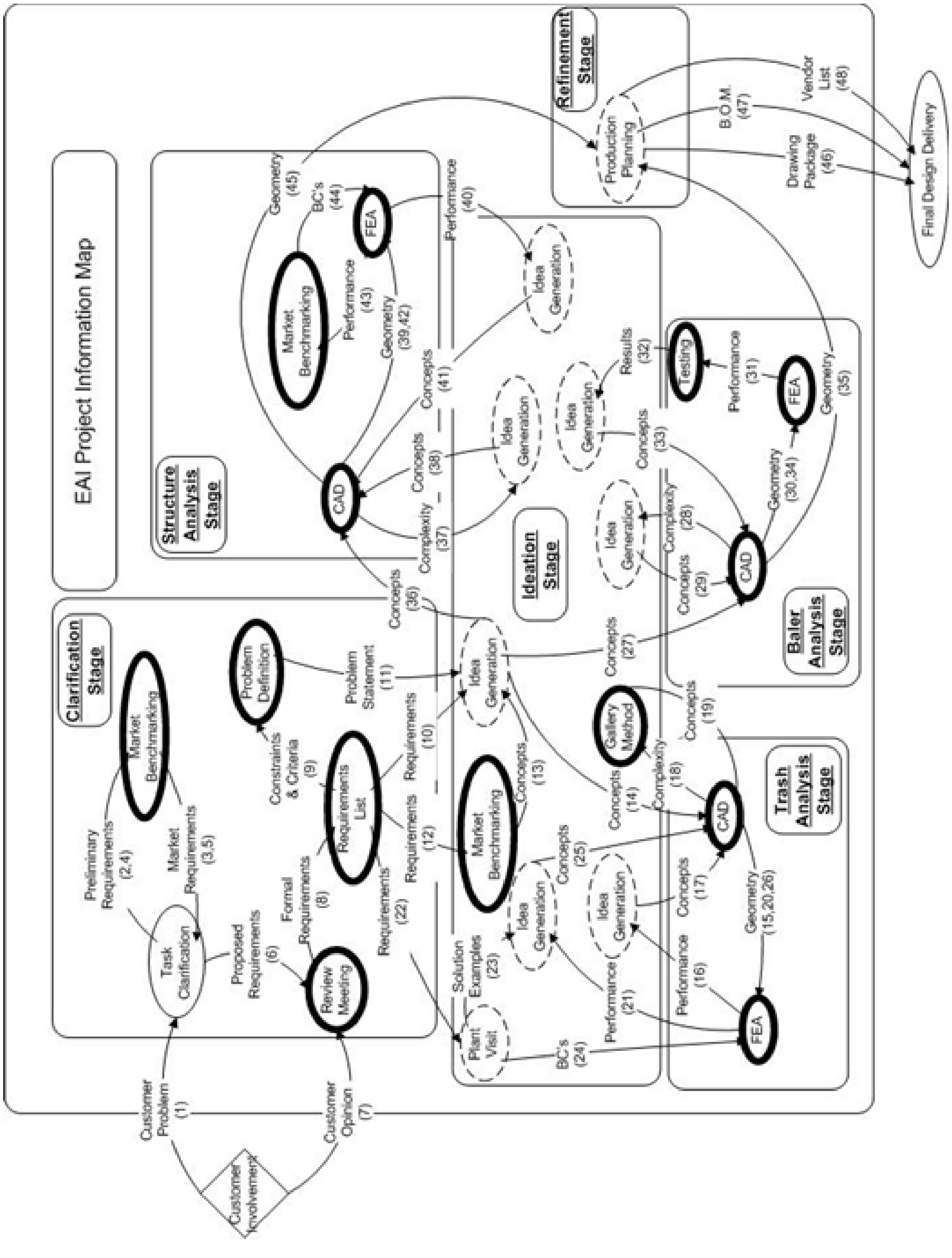
Appendix A: Generic DSM

Appendix B

Activity	Input	Category	Output	Category	Resources	Example
task clarification	customer problem	Requirements	preliminary requirements	Requirements	People	engineer
	market needs	Requirements	proposed requirements	Requirements	Computer	Dell
					Software	MS Word
market benchmarking	preliminary requirements	Requirements	market needs	Requirements	People	engineer
			concepts	Concepts	Computer	Dell
			boundary conditions	Requirements	Software	Firefox
Review Meetings	Proposed Requirements	Requirements	Approved requirements	Requirements	People	Customer
	customer opinions	Requirements	constraints and criteria	Requirements	Hardware	Projector
					Software	MS Powerpoint
Problem Definition	system components	Requirements	problem statement	Requirements	Documentation	MS Word
					People	Engineer
ideation	Requirements	Requirements	concepts	Concepts	Computer	Dell
	problem statement	Requirements	needed info	Requirements	Software	MS Word
	performance	Results			People	Engineer
	results	Results			Imaging	Paper
	complexity	Results				
Plant visits	needed info	Requirements	concepts	Concepts	Vehicle	Truck
			BC's	Requirements	People	Manager
					Hardware	Camera
CAD	concepts	Concepts	geometry	Concepts	People	Engineer
					Computer	Dell
					Software	SolidWorks
FEA	geometry	Concepts	Performance	Results	People	Engineer
	BCs	Requirements			Computer	Dell
					Software	Solidworks
Testing	needed info	Requirements	results	Results	People	Engineer
			BC's	Requirements	Hardware	Sensors
					Materials	PET bottles
Production Planning	geometry	Concepts	drawing package	Concepts	People	Engineer
			BOM	Concepts	Computer	Dell
			Vendor List	Concepts	Software	Solidworks
					Imaging	Paper

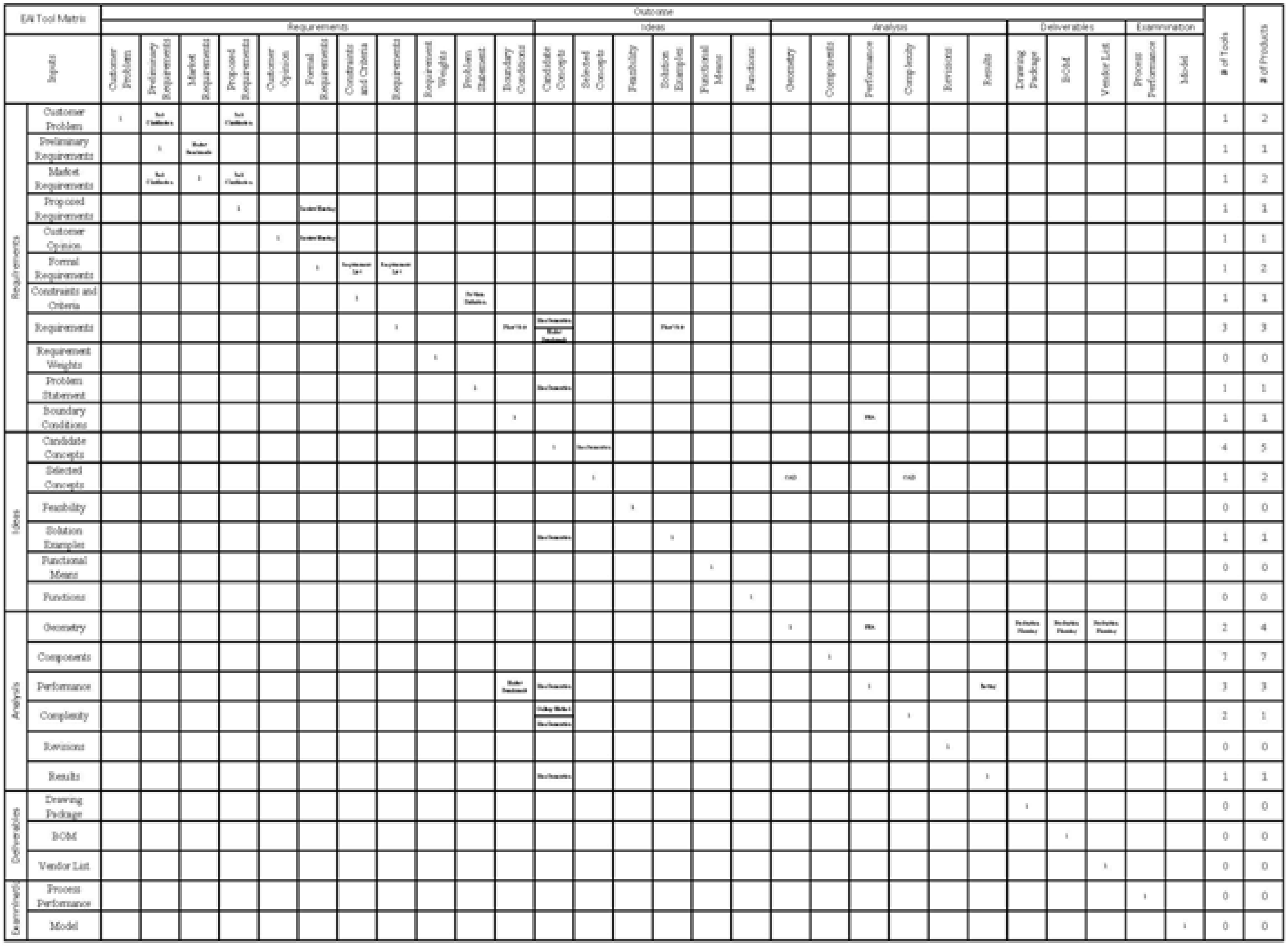
Appendix B: Assorted Design Tools and Design Methods

Appendix C



Appendix C: EAI DEIM

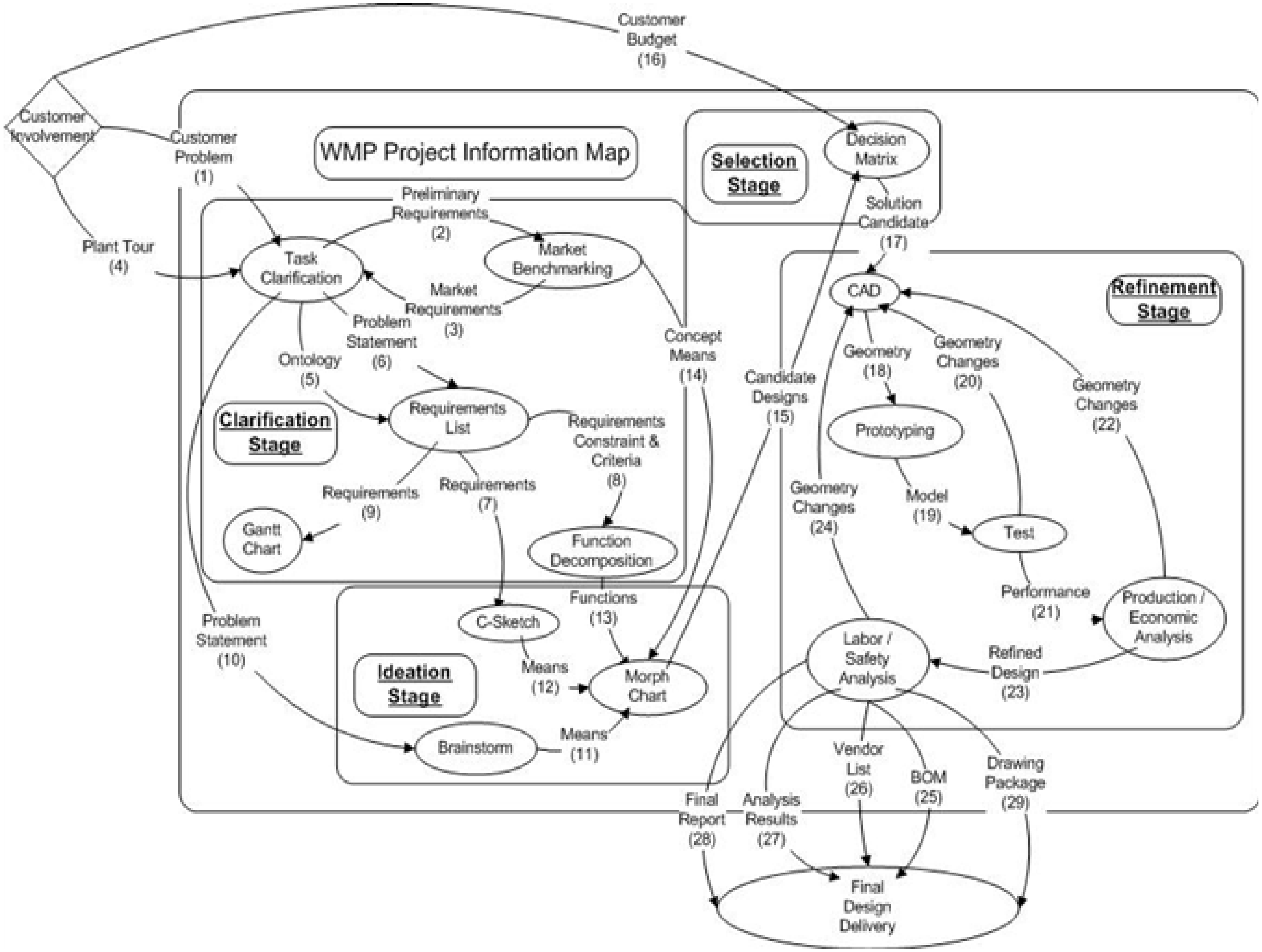
Appendix D



EAI Tool Matrix		Outcome																												# of Tools	# of Products
		Requirements											Ideas						Analysis						Deliverables			Examination			
	Inputs	Customer Problem	Preliminary Requirements	Market Requirements	Proposed Requirements	Customer Opinion	Formal Requirements	Constraints and Criteria	Requirements	Requirement Weights	Problem Statement	Boundary Conditions	Candidate Concepts	Selected Concepts	Feasibility	Solution Examples	Functional Means	Functions	Geometry	Components	Performance	Complexity	Revisions	Results	Drawing Package	BOM	Vendor List	Process Performance	Model		
Requirements	Customer Problem	1	[illegible]		[illegible]																									1	2
	Preliminary Requirements		1	[illegible]																										1	1
	Market Requirements		[illegible]	1	[illegible]																									1	2
	Proposed Requirements				1		[illegible]																							1	1
	Customer Opinion					1	[illegible]																							1	1
	Formal Requirements						1	[illegible]	[illegible]																					1	2
	Constraints and Criteria							1			[illegible]																			1	1
	Requirements								1			[illegible]	[illegible] [illegible]			[illegible]														3	3
	Requirement Weights									1																				0	0
	Problem Statement										1		[illegible]																	1	1
	Boundary Conditions											1									FEA									1	1
Ideas	Candidate Concepts												1	[illegible]																4	5
	Selected Concepts													1					CAD			CAD								1	2
	Feasibility														1															0	0
	Solution Examples												[illegible]			1														1	1
	Functional Means																1													0	0
	Functions																	1												0	0
Analysis	Geometry																		1		FEA				[illegible]	[illegible]	[illegible]			2	4
	Components																			1										7	7
	Performance											[illegible]	[illegible]								1			[illegible]						3	3
	Complexity												[illegible] [illegible]									1								2	1
	Revisions																						1							0	0
	Results												[illegible]											1						1	1
Deliverables	Drawing Package																								1					0	0
	BOM																									1				0	0
	Vendor List																										1			0	0
Examination	Process Performance																											1		0	0
	Model																												1	0	0

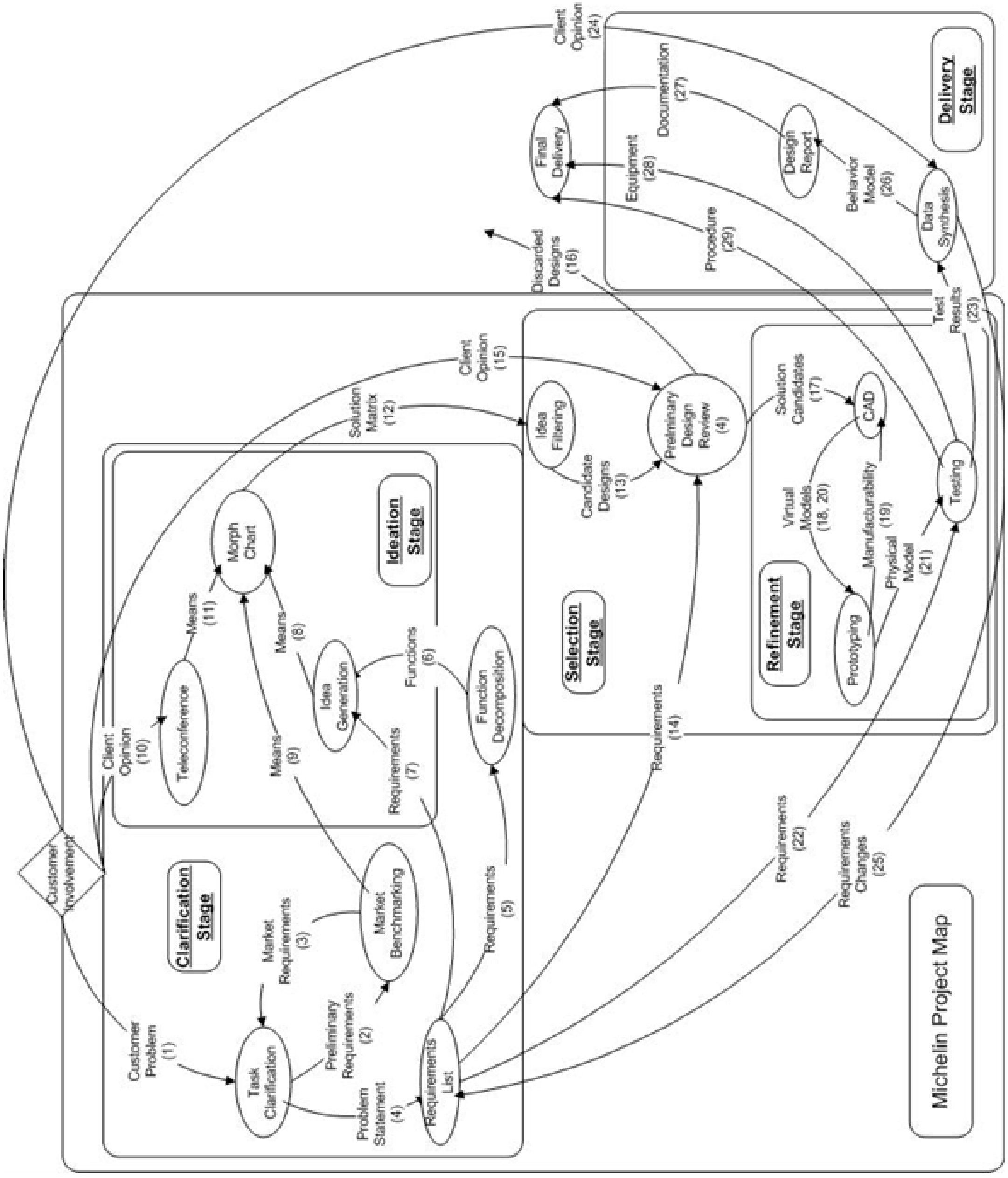
Appendix D: EAI DSM

Appendix E



Appendix E: WMP DEIM

Appendix F



Appendix F: Michelin DEIM

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