Decision-Thinking in PLM

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1. Introduction

The statement "Design is the evolution of information punctuated by decisions" first appeared in The Journal of Engineering Design in 2001(Ullman 2001). Now, ten years later, Product Lifecycle Management (PLM) has evolved to do a superb job of managing design information and is moving toward robust decision management. This paper explores a decision-centric view of product development and implications for PLM capabilities needed to fully punctuate the entire product life cycle.

The points made in this paper are based almost entirely on the results of research into how people do design and make decisions. Some of the references are for work done by the first author beginning in the 1980s. His focus began with efforts aimed at understanding how engineers design products from a cognitive viewpoint and they matured to developing methods to support team decision making activities. This body of work was intended, from the beginning, to support systems that could manage design information – exactly what PLM does.

To put the "information" component of the opening statement into context, consider the information pyramid (Ullman 2006a). The simplest form of information, at the base of the figure, is raw **data**. Data are numbers, text, drawings, geometric models or other descriptive information about some object or idea. **Models** define **relationships** between data. These relationships may be mental pictures of a situation, math equations, complete sentences or paragraphs, or graphic images that relate basic data and result in a richer form. These models produce more data and through understanding and interpreting the **behavior** of models there is the gain of **knowledge.** Finally, when your knowledge is sufficient, you can make **decisions** using **judgment** based on this knowledge. Supporting decision making requires that you manage data, models, and knowledge, as well as the associated judgment upon which your decisions are based.

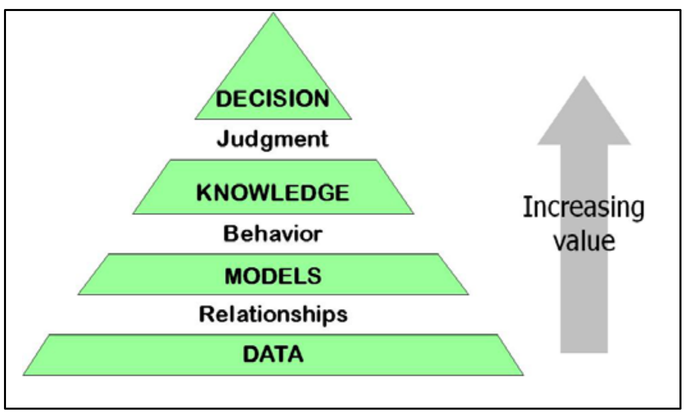

Figure 1: The Information Pyramid

Computer systems were first developed to manage data and simple models, and over time they have grown into powerful tools for the creation and management of these types of information. In many situations computers can manage knowledge. However, judgment and decisions have characteristically been very human activities. This paper focuses on how computers, and PLM systems in particular, may begin to support the entire information pyramid.

> Implication for PLM:
> PLM systems should enable the capture, management and query of information at all levels in the Information Pyramid.

A product is the sum of a stream of decisions. The product's function, its form and how long it takes to develop and manufacture all evolve from the quality of these decisions. Where PLM captures data and models, knowledge and decisions are notoriously hard to capture. Knowledge is often in the heads of those involved in the decisions, and afterwards it is likely that only the results of the decision-making remain. This may not be sufficient, as legal and government requirements all push toward decision thinking, traceability, and management.

If design is the sum total of the decisions made, then cost and time overruns are also a factor of the quality of these decisions. Consider, in one government agency that develops bleeding edge technologies, cost overruns ranged from 31% (small projects) to 315% (very large projects) (Ullman 2006a, page 75). Or, in the Chaos Report, (Standish 2009) an annual analysis of information technology (IT) projects; 44% of all 2008 IT projects were delivered late or over budget and an additional 24% were cancelled. Only 32% of projects completed were on time and on budget with full functionality. It should be noted that the *Chaos Report* data may actually be understated, as they are self-reported. Generally, project failures are thought of as management problems. But they are problems of poor decision-making. Specifically, for the government agency, there are clear points in the decision-making process used in budgeting the projects that leads to the poor results and a change in this process has reduced the overruns significantly (Chmielewski 2009).

Supporting the view that it is the decisions that drive project success, consider the study in *Why Decisions Fail,* (Nutt 2002). This book describes a study of 400 decisions made by senior managers in medium-to-large organizations. The decisions these managers made included a mix of analytical and experimental information, expert opinion, and gut feel. The primary indicators of decision success were 1) whether or not anyone took action after the decision was made and 2) whether this action was still in effect two years later (i.e. did the decision stick). The study found that *fully half the decisions had failed*—either action was not taken, or it did not stick. Of the decisions that failed, the only effect observed two years later was the use of resources—time, money, personnel, equipment, etc.—all expended without achieving success in attaining the original goals. In other words, fully half of the decisions made were not robust: They were not able to withstand uncertainty, conflict, and change, nor did they elicit the buy-in necessary to make them a success.

According to Nutt, three main classes of "blunders" doom decisions. These blunders can lead to lead to a variety of issues including cost/schedule overruns and functional changes. Decision makers' first blunder is that they use failure-prone practices in two out of every three decisions they make. Further, they seem oblivious to the poor track record of these practices and seldom study their failures. In other words, the process that was followed (whether good or bad) was not captured and could not be replayed for reuse or study.

The second blunder is basing many decisions on premature commitments; decision makers jump on the first idea that comes up. In other words, many decision-making activities are actually only efforts to justify a premature conclusion, as opposed to using evidence to select the best possible alternative.

The third blunder is that people spend time and money on the wrong things: tasks that do not add value to making the best possible decision. In other words, they don't have a strategy that helps them determine what-to-do-next.

While Nutt's work was business based, it is no different in product development. Thus, it is worthwhile to take a decision centric view of the product lifecycle in order to determine what characteristics PLM needs to keep product development from Nutt's "blunders."

> Implication for PLM:
> To improve decision success, PLM systems should help designers reuse prior decisions, present information to slow premature commitments and help users determine what to do next.

2. Decision making

Keeping with statement "Design is the evolution of information punctuated by decisions", this paper takes a decision-centric view of the product life cycle. With this view, the information stored in documents and in stakeholders' heads is used to fuel decisions, each of which produces new information in terms of the choices made, the commitment of resources, and the need for new information and questions to be answered through other decisions. It is the interrelationship of decisions and the process of making them that are key here.

Decision-making Definition

At its most basic, a decision is an irrevocable allocation of resources (Howard 1966). The resources are directed at an alternative chosen from amongst many to satisfy criteria that represent an ideal resolution to the issue at hand. Determining criteria satisfaction is the challenging part as the information for evaluating how well each alternative meets each criterion is usually uncertain, incomplete and evolving. Further, each stakeholder – a party with a vested interest in the decision made – may have a different set of values about which criteria are important and the evaluation results. This is only compounded by cultural and professional stakeholder differences. This three element model of decision making: (1) a set of action alternatives; (2) criteria that reflect preferences over the possible outcomes of alternate actions; and (3) beliefs about the world – information needed to evaluate the alternatives versus the criteria – date from the 1950s (Savage 1955) and is the backbone of all decision research and theory.

Applying this to PLM, decision thinking leads away from focusing on objects and functions to focusing on this information as alternatives, criteria, evaluations and other decision objects. Decision-thinking serves two primary purposes in PLM: 1) supporting the evolution of the product during its life cycle, and 2) supporting the ability to find information about its structure, operation and purpose for later support, change and reuse.

Support for the product evolution process

As will be shown, there are literally thousands of decisions made during the lifecycle of a product. Many of these greatly affect the time-to-market, cost and operation of the product. It is important to ensure that these decisions are of the best quality possible, with the information that is available. What makes these decisions hard is that they are based on uncertain, incomplete, evolving information emanating from a variety of stakeholders (e.g. customers, engineers, salesmen, suppliers, regulatory entities, etc). These stakeholders, by definition, will not agree on what is important or even on the interpretation of information. Complicating matters further, the stakeholders may be cross-cultural and will certainly be cross-discipline. Finally, they may be meeting synchronously (at the same time, co-located or remote) or asynchronously (not face-to-face, not at the same time) as material is gathered and decisions made.

True, a good information management and communication system, which is common in PLM, can go a long way to support the decision-making process. However, this paper will present and develop strong evidence that the currently available information management and communications systems are not enough. Additionally, the last section of the paper focuses on methods to directly support the decision-making process, ones that are not currently integrated in PLM systems.

Capture rationale and enable query of past decisions

The second reason for managing decision information is rationale capture and query. A rationale is the fundamental reasons for the choice made. This must include all the information on the design pyramid that went into the decision. By capturing this information in a usable form, it can be queried to answer questions about form, function, the alternatives considered, why they were chosen or rejected, the reasoning behind choices, etc. There are at least twenty-three types of queries made of rationale information (Ullman 1998).

To show how important this is, a researcher observed engineers at the Civil Aerospace Division of Rolls-Royce and found that only 30% of the queries were answered from documents and drawings, the other 70% were from colleagues' memory (Bracewell 2009). The 30% value was an improvement over a finding of 15% three years earlier. During another study on the information requests of working engineers, (Kuffner 1991) it was found that when presented with drawings for a totally mechanical device and asked to make changes, about 2/3s of the queries were geometric and the other third were about the operation or purpose of objects. Further, the subjects studied felt quite unsure of their queries regarding purpose,(e.g. "why is this….") and looked beyond the drawings and other documentation to (i.e. colleagues) for answers.

However, the memories of colleagues is often just plain wrong. In one experiment (Plous 1993), a group was asked two weeks after a meeting to recall specific details of it. In recounting the meeting they:

- Omitted 90 percent of the specific points that were discussed.
- Recalled half of what they did remember incorrectly.

- Remembered comments that were not made.
- Transformed casual remarks into lengthy orations.
- Converted implicit meanings into explicit comments.

Further, it is well known that with the retirement of the baby boomers, knowledgeable colleagues are leaving the workforce and captured information will increasingly be needed.

Implication for PLM: PLM systems must capture and make available information in a form and language that is consistent with the decision need, relieving the reliance on human memory.

Types of Product Development Decisions

In this paper, the basic building blocks of all decisions are essentially the same as will be developed. Nonetheless, the ultimate reason for decisions during a product's life cycle is often one of the following:

- **Design Alternative Decisions:** For each part, feature, function choose the alternative with the highest potential for satisfaction. The book *Making Robust Decisions* (Ullman 2006a) focuses on these choose-one-from-many decisions.
- **Acquisition Decisions:** Choose the best system to purchase. This is a form of design alternative decision, but is usually focused on outsourced items. The importance of making robust acquisition decisions has become so important that DoD and OMB have specific guidelines for justifying decisions, generally called - Analysis of Alternatives (AoA). AoA is further discussed in the next section of this paper. A sub-set of an acquisition decision is a make/buy decision – should the part or assembly be made in-house or acquired from a vendor.
- **Portfolio decisions:** Portfolio management is a dynamic decision process, where a list of projects is constantly updated and revised, and those most satisfactory are funded while the others are dropped. The portfolio decision process is characterized by uncertain and changing information, dynamic opportunities, multiple goals and strategic considerations, interdependence among projects, and multiple decision-makers and locations. (Ullman 2009c)
- **Trade off Decisions:** A trade study (or trade-off study) is the activity of a multidisciplinary team to identify the most balanced technical solutions among a set of proposed viable solutions. During every stage of the design process, designers trade off performance, cost, and risk in an evolutionary process whose goal is to find a satisfactory solution. Trade studies are essentially decision-making exercises - choose an optional concept or course of action from a discrete or continuous set of viable alternatives (Ullman 2006b).

The wording of these descriptions makes it sound as if they are mainly systems level decisions, but in reality they occur at many levels of granularity.

Implication for PLM: There are many types of decisions made during a product's life cycle. PLM can be general enough to support all types of decisions and/or supply templates to help support critical decisions.

Decision Granularity

Decisions range from those made by a team that affects the very architecture of the entire system, to those made by an individual engineer on the very smallest detail. Where a major system level decision may require a management team many months to make, every high level decision is composed of literally thousands of finer grained decisions. A study of individual engineers designing products included recording their activities and dissecting them on an utterance and line-by-line basis. One finding of this study was that, at their finest, detailed decisions occur once per minute (Stauffer 1991). This is keeping with human's cognitive limitations and the generally accepted understanding that, in order to solve problems and make decisions we must divide them into very small pieces, address each one and then fuse the results together. This applies to a single designer sitting at a computer or a management team meeting to make a system level decision.

In workflow, we usually think of decisions as made at gates in a stage/gate process. However, the gate is actually the sign-off on many sub-decisions made during the stage. Each may be as important as next and, while it may not be necessary to vet each decision, it is important to be able to query them and understand why they were made.

What is important is that each detailed decision is affected by constraints that result from other decisions made at higher levels and assumptions made in other concurrent work. The robustness of every higher level decision is affected by the results of thousands of detailed decisions that enable it. Regardless of level of granularity (from the architecture to the smallest detail), the decision-making structure remains basically unchanged.

> Implications for PLM:
> Small decisions are often as important as large decisions. Attention must be paid to decisions at all levels of granularity. This does not imply that every minute-by-minute decision needs to be supported but those that are important must be.

3. The Structure of Decisions

Decision-Making Structure

At its most basic, decision-making is a process of searching for a satisfactory object, function or course of action to resolve an issue or answer a question. The exact "process" used changes with the circumstance. It is important to understand these processes as they determine the quality and the rationale for the choice.

There has been a recent spate of best-selling books that support the notion - go with your gut when making a decision (e.g. *Blink : The Power of Thinking Without Thinking* by (Gladwell 2005), *Gut Feelings* (Gigerenzer 2007) and *The Power of Intuition: How to Use Your Gut Feelings to Make Better Decisions at Work (Klein 2004)*). Intuitive decisions are based on prior knowledge and experience and don't need justification (if you are right). Although the authors suggest that business decisions can be made based on gut feel, in actuality they can only be useful when at least one of the following occur:

- One person is responsible for the decision and their knowledge is high (e.g. "I always use a 10/40 screw to hold two plastic case parts together.")
- Time is short (e.g. "The test system is crashing, turn it off, quick!")

or

- Consequences of a poor decision are low (e.g. "The color of this makes no difference, it is inside a sealed case.").

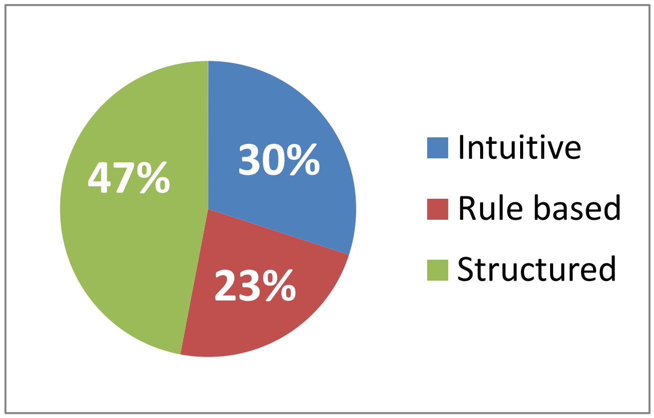

Figure 2 Decision-making processes (Stauffer 1991)

In a study of individual designers developing new products, 30% of the decisions made were of this, intuitive type (Stauffer 1991) (See Figure 2). Since these decisions are made rapidly, even unconsciously, they can not be caught by a PLM system. Generally, if they are important to someone else or the consequences are significant, then a more complex process will be used.

A second decision process is rule-based where knowledge is in terms of if/then rules. Sometimes these are formalized in design standards; sometimes they are personal, based on knowledge and experience. Rules can be about the design process itself, or the form or function of the product. In the study of individual designers, 23% of design decisions were rule based. When the designer was faced with a situation and it matched a rule, the rule was followed. The problem with rules is that they are fragile, the "if" part of the rule may not apply exactly and thus the "then" is wanting.

The remaining 47% of the decisions made by the individual engineers in the experiments used a structured process. In the reference (Stauffer 1991) the researchers identified three different structures that only differ in details. The key point is that they all are a controlled search through the design space that includes the following types of information (further refined in the next section):

1. Determine a set of **criteria**, a representation of the ideal result. These are often called requirements, specifications or constraints. The importance of these are usually dependent on stakeholder values
2. Generate **alternatives**
3. Use **evaluation** to judge how well the alternatives meet the criteria
4. Determine the **satisfaction** for each alternative including the risks inherent in it
5. Decide the **rationale** for what to do next – choose an alternative or refine the criteria, alternatives or evaluations

Unless reacting intuitively or following a rule, these five decision-making elements are addressed either informally or formally in all decision making, regardless of granularity and regardless of whether an individual or a team is performing the work. At its simplest there is a single criterion. A single alternative is generated, evaluated relative to it, found acceptable and chosen. (e.g. I need a 3mm pin, 2 cm long and a search returns a single SKU that will work.). More generally there are multiple criteria and alternatives.

As the granularity increases and the consequences increase, there is the need to include more stakeholders and develop new knowledge (in the sense of the information pyramid in Figure 1). These complexities require more formal structured methods. These all have the same five decision-making elements and they are all, at their finest composed of finer grained sub-decisions.

> Implication for PLM:
> Where PLM can not and should not capture the moment-by-moment intuitive decisions, it must support both rule-based and structured decisions with easy information capture and query.

Government efforts at requiring decision-focused effort

Governments are noted for budget and time overruns. To try to control these overruns, the Office of Management and Budget (OMB) and the Department of Defense (DoD) have adopted Analysis of Alternatives (AoA) to ensure that multiple alternatives have been analyzed prior to making investment decisions. AoA is an assessment approach to evaluate potential solution sets (material, organizational, structural, or ideological) relative to a desired capability. An AoA study moves from the justification of a single alternative to the exploration of multiple options in order to establish a basis for funding the best possible projects in a rational, defensible manner while considering risk and uncertainty. To enable discussion, four levels of AoA maturity have been identified (Ullman 2009a, 2011):

- Level 0 – Propose one alternative and justify it.
- Level 1 – Propose multiple alternatives and provide a one-dimensional comparative analysis with some inclusion of uncertainty effects.
- Level 2 – Propose multiple alternatives and provide multi-dimensional comparative analysis with some inclusion of uncertainty effects.
- Level 3 – Propose multiple alternatives, and provide multi-dimensional comparative analysis and support robust resource allocation decisions with the inclusion of uncertainty effects.

Where many government projects of the past were Level 0, Part 7 (Section 300) of the OMB Circular A-11 (OMB 2008) establishes a policy for planning, budgeting, acquisition, and managing Federal capital assets, and gives instructions on budget justification and reporting requirements. This policy is an effort to move organizations from justifying a single alternative (Level 0 AoA) to the comparison of multiple alternatives using Net Present Value as a single measure (Level 1). Within the OMB and other government agency literature, AoA is often referred to as “Alternatives Analysis.” Details on Alternatives Analysis are given in Appendix A of GSA’s IT Budget Submission Instructions (GSA 2007).

Perhaps the best documented AoA methodology and approach is detailed in the Air Force Materiel Command Analysis of Alternatives (AoA) Handbook (USAF 2008). It is a handbook of useful analysis tools and techniques that define a Level 2 AoA. In DoD, AoAs are done at different milestones in the acquisition process: at the start of the first phase (Concept Refinement); a Design Readiness Review made in the third phase (System Development & Demonstration); and a Full Rate Production Decision Review made in the fourth phase (Production & Deployment). DoD AoA studies are accomplished by a study team made up of members with appropriate skills drawn from many organizations. Members often include contractors who provide critical skills and resources. The team focuses on defining alternatives, then assessing and comparing their operational effectiveness, life cycle costs and risks. The effectiveness of AoAs will be seen as the decision making details are explored.

Implication for PLM: Analysis of Alternatives is a prevalent decision making methodology. PLM should support AoA Level 3 maturity.

4. Decision Information

There are five decision-making information types: alternatives, criteria, evaluations, satisfactions and rationale for what to do next (Figure 3). It is tempting to call these "decision-making steps", but they are not necessarily sequential. These five are the classes of product development information needed to support structured decision-making and the later understanding of choices made. Each element is discussed in this section.

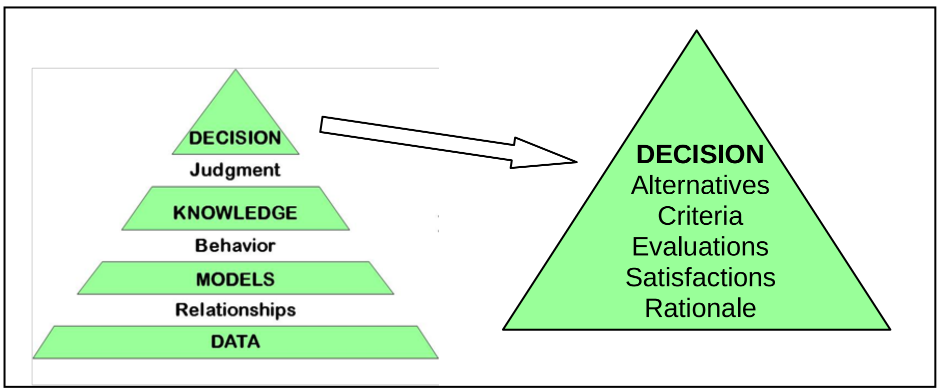

Figure 3: The Peak of the Information Pyramid Detailed

Alternatives Considered

If you only have one alternative to consider, then you don't have any decision to make, you only have justification. The sensitivity of the project results to the number of alternatives considered is striking.

Consider the results of a study done in Germany using individual designers developing a simple mechanism on paper (Dylla 1991). The researchers designed the problem so that there were three sub systems. One sub-system had two reasonable alternative mechanical solutions. The second and third sub-systems had three each. Thus, the total design space consisted of 18 different possible configurations. Six subjects independently solved this problem. At the end of their work all the solutions were rendered in a consistent manner on a CAD system and in hardware. These results were judged by a panel of profession engineers. The panel knew nothing about the details of each subject's solution beyond the initial requirements and the drawings and hardware presented. The panel gave each solution a technical quality score between 0 and 100%. One subject, who only generated 5/18 alternatives received a technical quality score of 47%. Two subjects, who explored the design space considering 12-13 of the options, were each scored at 80%. The other three subjects fell in the middle distributed along a straight line connecting these end points. The result of this experiment shows that doubling the percentage of the design space explored, doubled the technical quality of the results.

While the above result was for a simple system with a single designer, similar results occur for large systems. Earlier we introduced Analysis of Alternatives, a method to help OMB and DoD make good acquisition decisions. Both these agencies require at least four alternatives (the current system plus three options) be considered for system acquisition.

In 2009 the GAO was tasked with studying how well AoA efforts ensured that DoD projects met time and cost targets (GAO 2009 (raw data) and (Ullman 2011 (reduced data)). To accomplish this, the GAO studied 32 major acquisition projects. Each was classified as having either low, medium or high cost/schedule growth. Of the 32 projects the GAO studied, there was no formal AoA in ten of them. Of these, seven were updates of earlier projects or were supported by other analyses. For the other 3, high cost and schedule growth occurred. Of the remaining 22 projects, 13 had a Narrow Scope of Alternatives and of these only 31% resulted in Low Cost and Schedule Growth (see left side of Figure 4). Meanwhile the nine that included a Broad Scope of Alternatives resulted in 78% with Low Cost and Schedule Growth (right side of Figure 4). The GAO never fully defines “broad” and “narrow”, but even with a liberal interpretation, the point is made – consider more alternatives and double your chances of being on cost and schedule target.

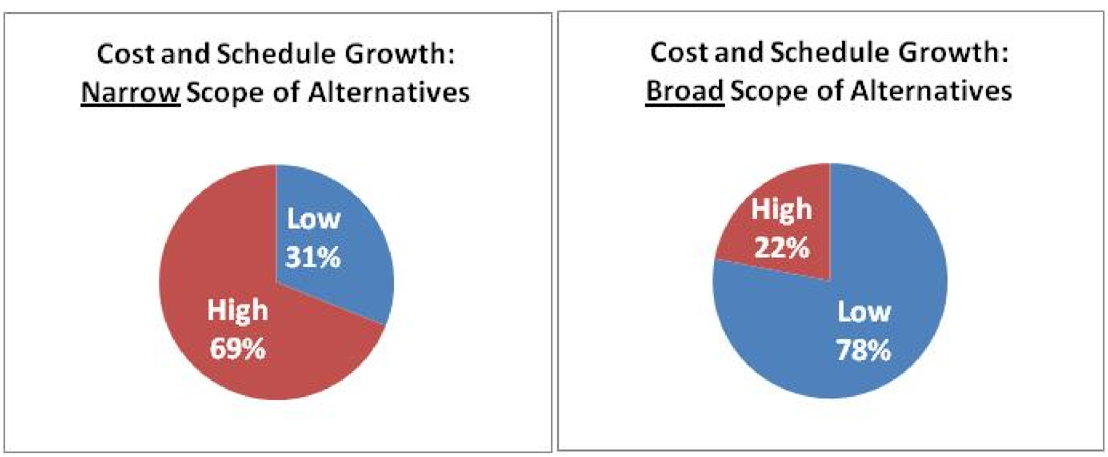

Figure 4: GAO findings on Alternative Development

Three additional results from the GAO study are worth discussing: First, Choosing an alternative too early exacerbates overruns. Of the six projects that chose too early, each of the four that did not develop sufficient alternatives or provide adequate risk assessment (see section below on Evaluation) then had moderate to high cost/schedule growth. In these four, the program sponsors had decided on a preferred solution prior to the AoA. The AoA was more of a justification exercise than for decision support. The two projects that, in spite of early selection, still had time to explore multiple alternatives and perform adequate risk assessment, had low cost/schedule growth.

Second, in nine projects, the AoA study was compressed or concurrent with other activities. Seven of these also did not develop sufficient alternatives or adequate risk assessment. Of these seven, six had high growth due to limited time committed to the AoA study. The two that still had time to explore multiple alternatives and perform adequate risk assessment then had low cost and schedule growth.

Third, of the 22 projects, 9 were provided with late or no AoA guidance at all. Of these nine, six did not develop sufficient alternatives or adequate risk assessment. Of these six, five had high cost/schedule growth. Of the three that explored multiple alternatives and performed adequate risk assessment, two had low cost/schedule growth. In all, only 33% without guidance had low cost/schedule growth.

What is somewhat troubling about these GAO results is that CAD, a major component of PLM, has the reputation of stifling the creation of multiple alternatives. One study that addressed this reputation (Robertson 2009) was based on a survey of 255 designers. The typical respondent was male, with an undergraduate degree, had more than 7 years of experience as a designer, and worked in a small team. They represented 31 countries with the vast majority using solid modeling most of the time. The study focused on the effects that CAD use has on the creativity of the designers in terms of: 1) enhanced visualization and communication, 2) circumscribed thinking, 3) bounded ideation, and 4) premature fixation.

Where the survey results show that CAD greatly enhances visualization and communication, it also shows that during early design stages, where multiple alternatives are most needed, designers over-use CAD. The importance of this is reflected in the other measures. Further, it shows that CAD use encourages individual work over group work, and individual problem solving over group problem solving, two detriments to robust decisions.

Circumscribed thinking arises when CAD use constrains (i.e. circumscribes) the thinking and problem solving of the designer. The effect of this is clear in a quote from one subject “... I can walk through a store and frequently tell what software certain products were designed in.” The effect of this on alternative generation is not clear.

Bounded ideation occurs when the constant use of CAD under stressful conditions negatively affects the motivation, and hence the ability to generate multiple alternatives. The survey results indicate that most CAD users are not affected, or are only mildly affected, by this.

Premature fixation directly affects the number and quality of multiple alternatives. What they found was that when CAD is used in the early, conceptual stages of design, it is effectively used as a drafting tool, for computer-based sketching. It is only in the later stages that it is used in the way that the CAD developers had intended, as a fully-fledged "design" tool.

The study showed that the reputation of CAD for stifling multiple alternatives is not well supported by the current generation of systems. Nonetheless, the study authors conclude that the best environment for idea generation tended to occur away from computers, in small meetings, characterized by large amounts of sketching and discussion. This implies that much of this critical information is not captured for reuse and review.

Implication for PLM:
PLM tools should encourage the development of multiple alternatives for critical issues and enable easily finding them later to support the rationale, regardless of the development medium. Further, since alternatives change with time, PLM should record both changes to and linkages between multiple representations of an alternative.

Criteria

The term "criteria" is used to mean the requirements, constraints or specifications that determine the measures that are being used to weigh the alternatives during evaluation. They may be quantitative (e.g., a budget that cannot exceed a certain amount) or qualitative (e.g., the design must be approved by the review committee).

Developing the criteria used for decision-making is a tricky thing. First, criteria are often unarticulated but are fundamental to the choice made. Second, in a team situation the criteria that are important to one party may not be the same as what is important to another. Third, the formal customer or design requirements that are commonly developed are often inadequate for decision-making.

Supporting this last point, ARM Research (ARM 2008) found that 46% of manufacturers listed "Product does not meet customer needs" as the reason product launch failures. This is due to the customer's needs not being reflected in the decision criteria and, even if they are, they are often insufficient. For example, Motorola released an RFP with over 60 specifications for an electro-mechanical device (Ullman 2005). These related to cost, mechanical and electrical performance, reliably and other engineering and business measures. Twenty proposals were submitted. The reviewer quickly divided these into two piles, those that met the requirements and those who did not. Then the hard part began - how to differentiate the five that did meet the requirements. The sixty requirements were all "filters", but Motorola was missing discriminating criteria, criteria that allow the close front-runners to be differentiated. Guidelines for developing decision criteria are in Ullman 2009b.

Even if the criteria are robust, they often are not used very effectively. In the German study referenced in the Alternative Section above, there is a significant relationship between the percentage of time spent analyzing the criteria, and the technical quality of the result. The technical quality of the products developed by the engineers who spent around 7% of their time understanding and developing criteria were judged to double that of those who spent 2–3% of their time developing criteria (The linearity of the 6 subjects' results was uncanny). The engineers didn't spend all their criteria time at the beginning of the task. In fact, the successful engineers worked hard to refine the criteria at the beginning and then revisited and refined them many times during the course of the experiment. This is not to say that a project should devote 7% to criteria development, but more time yields better results.

Finally, design decisions are transducers of criteria (Ullman 1991). In making a decision, some collection of existing criteria is input and new, derived constraints are output to act as criteria on future decisions. The refining of criteria can be seen in the results of an experiment that focused on the sources of constraints, Figure 5 (Ullman

1991). Here a video taped session of a single engineer designing a fairly simple mechanism was dissected and the criteria categorized as:

- **Given** external to the design as in design specs or customers' requirements
- **Introduced** through domain knowledge
- **Derived** by a prior decision

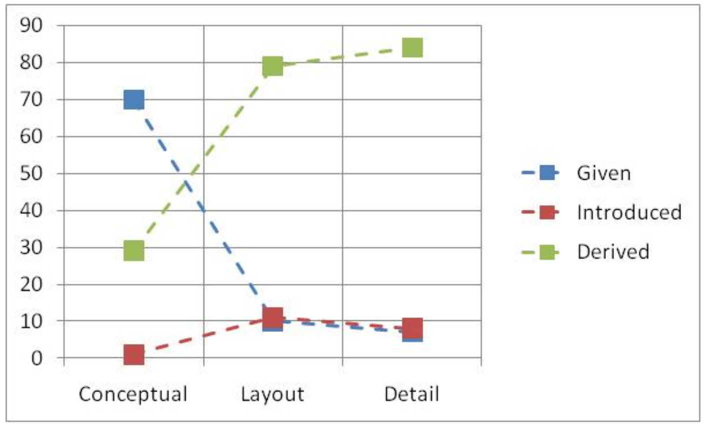

Figure 5: Sources of Criteria

A sub-assembly was studied that included 38 design objects (parts) with 277 form and functional features. Relating these objects and features were 725 constraints. The sources for these constraints over three phases of the assembly development are shown in Figure 5. Of course these percentages will vary from assembly to assembly, but the following is clear. When doing conceptual design, the criteria on design decisions come from customer requirements or the results of prior decisions, made external to the current effort. As concepts are laid out and detailed, a vast majority of the constraints are derived from prior decisions made in the design of the assembly. The decisions made during the evolution of the 38 design objects and their features put constraints on other objects and features both within this assembly and external to it.

Implication for PLM:
PLM tools must not only support the use of given or external requirements, but must additionally manage those introduced and derived in a form that can be easily accessed and used as criteria by decision-makers.

Evaluation

Evaluation methods, i.e. time and cost estimates, models, simulations, test results, and expert opinions, are all efforts to evaluate how well a proposed alternative will meet a criterion. They are only estimates of expected performance in an uncertain future and are only simplified versions of the real world. The measure of how well a model or simulation analysis represents the state and behavior of a real-world object is often called its fidelity. Back-of-the-envelope calculations are usually low fidelity, whereas detailed simulations—hopefully—have high fidelity. Experts often run simulations to predict performance and cost. At the early stages of their projects these simulations are usually at low levels of fidelity, and some may be qualitative. Increasing fidelity requires increased refinement and increased project costs. Increased knowledge generally comes with increased fidelity, but not necessarily; it is possible to use a high-fidelity simulation to model "garbage" and thus do nothing to reduce uncertainty. In fact most detailed – supposedly high fidelity cost estimates (the basis for OMB, Level 1 AoA analyses) are often little better than guesses. The accuracy of the data is suspect (sometimes off by an order of magnitude (Cooper 1998)).

To show how poor many evaluation estimates are, consider the results of a simple estimation exercise described in *Making Robust Decisions* (Ullman 2006a). Time estimates were made by about 200 attendees at a conference on how long it would take to clean a pile of dirty dishes. Even though the description of the situation was very detailed; complete with a photograph of the dishes, and instruction on how to clean the dishes was very detailed; and the task was an every-day experience for most estimators, the resulting estimates averaged 32 minutes with a standard deviation of 10 minutes. In other words over 30% of the estimates were more than 10 minutes more or less than the average. Further, by simply changing the wording of the estimate request, the average estimate dropped to 17 minutes. In other words, asking a single estimator for the time required to do a common task can result in an estimate that is not much better than a guess and, at best highly uncertain. This is true of all estimates, whether for time or any other measure, to some degree.

Where the past performance may be known, the present is obscured by its immediacy, and the future is a best guess. The best guess is clouded in uncertainty, and uncertainty results in risk - without any uncertainty, estimates will match reality, and the project will end on schedule, within budget and with all functions.

In the GAO study of AoA, another result was for the level of risk assessment including technical risk, programmatic risk, and operational risk. Twelve of the 22 projects that used AoA conducted Limited or No Risk Assessment for each alternative. Of these 12, 33% had Low Cost/Schedule Growth as shown in left side of Figure 6. The other 10 projects were judged to have Adequate Risk Assessment. Of these, 70% had Low Cost/Schedule Growth as shown in the right side of Figure 6. The GAO report concluded from these results that if AoAs do not examine risk, then they are likely to present overly optimistic assessments of the alternatives.

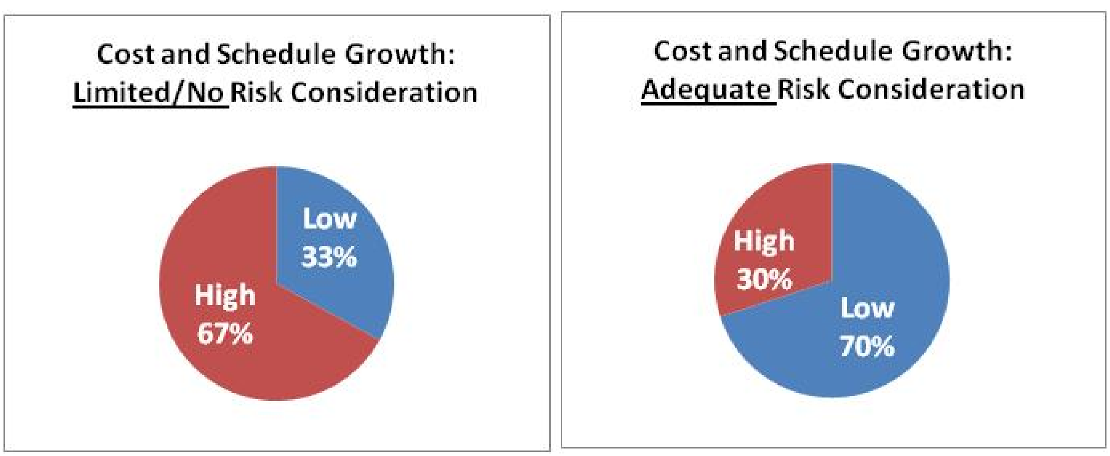

Figure 6: GAO results for Risk Consideration

Uncertainty, and thus the risk, can be reduced during a project only through the expenditure of resources (e.g. do more analysis to reduce the uncertainty). However, it is often just necessary to understand what the risks are and to account for them when making a decision. One approach for understanding risk in a project is to develop a Risk List (Chmielewski 2009) in which each uncertainty, concern or potential obstruction to the implementation and success of alternative relative to each criterion is itemized. Some of the risks itemized will be technical and some programmatic. Programmatic risks are tough to account for but can have great affect on a decision and subsequently the project. Non-managers dislike predicting programmatic risks and managers tend to be optimistic and believe that they will handle programmatics. “I will not let the old problems happen to my project!” There is often some historical documentation on past technical problems but not on programmatic problems.

A second method is to account for uncertainty during decision-making. This can be done by treating evaluation results as a distribution rather than a deterministic point value. One method for easily accounting for uncertainty in decision-making will be introduced in the section on Decision-Thinking Technologies.

> Implication for PLM:
> PLM tools must help developers and managers understand, track and manage estimation uncertainty and risk.

Alternative satisfaction

Decision theory prescribes that the optimal action is to choose the alternative with the maximum satisfaction relative to the criteria. We do this all the time, however informally. This is not too hard when there is only one criterion and the decision is independent of other issues. Reality isn't kind with multiple criteria, stakeholders, uncertainty and other complications. Much research has gone into how to support finding satisfaction in these complex situations as will be addressed in the final section of this paper.

Rationale for what to do next

As important as it is to choose an alternative, it is equally important to learn what to do next. The decision making process should help in guiding work toward identifying the best possible alternative. A simple model is given in Figure 7 (Ullman 2006a, page 246) that gives guidance for six potential outcomes. The first (#1) is to choose the best alternative and move on. The next four (#2 - #5) encourage refining the other types of information. The final outcome (#6) suggests that criteria generate new issues. For example, if clarification is needed on some measure (i.e. criteria) during alternative evaluation, then study of this measure becomes a new issue with multiple alternative results. What is important here is that, often people do what it is they know how to do rather than what is important to reaching a decision. Effectively, asking “what should we do next to reach a decision” is a form of cost/benefit analysis that guides decision-making.

To capture the decision rationale, the reasons behind a decision, means to save all of the types of information discussed in the sections above in a manner that can be searched and related to specific decisions. Even the simplest PLM system can capture the documentation for alternatives, but tying these to the criteria, evaluations, uncertainty/ risks, satisfactions and what-to-do-next requires a decision-centric system. Some systems that address this need are discussed in the next section.

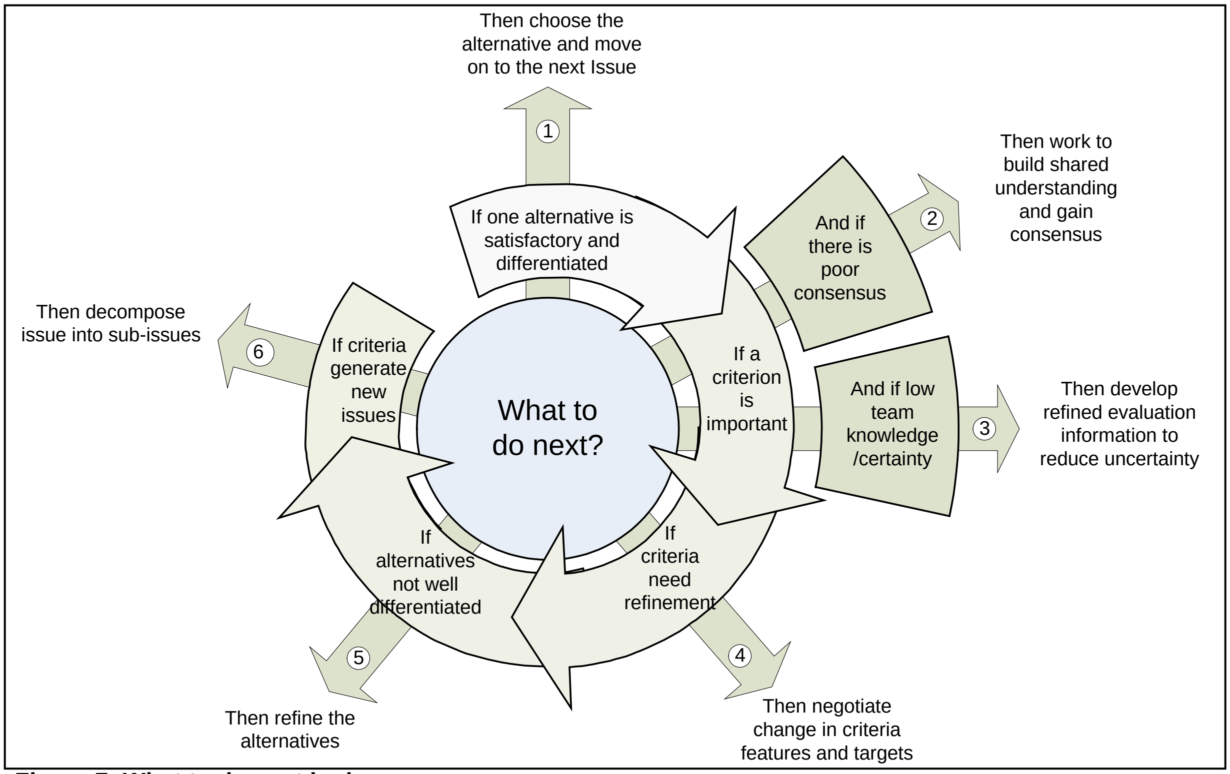

Figure 7: What to do next logic

Implication for PLM:
Being able to capture and query the rationale behind decisions means being able to record the information that fueled the decision. PLM tools need not only to associate information with objects and functions, but with the role played in specific decisions.

5. Decision-Thinking Technologies

Technologies that can help manage a decision-centric approach to product development and management need to support all of the types of information described in the Information Pyramid (Figure 1), especially the decision-centric information in Figure 3. Where PLM systems do support many of these types of information, there are two decision-thinking technologies that have not yet been integrated into the PLM fold.

To introduce these and their implications on PLM, realize that decision support is not the same as support for decision-making (ARM 2008). Decision support has been embodied for many years in Decision Support Systems (DSS). The main purpose of a DSS is to gather and consolidate data in order to provide management with aggregated information regarding the product lifecycle (Golovatchev 2007). Such systems are intended to help decision makers compile useful information from a combination of raw data, documents, personal knowledge, or business models to identify and solve problems and make decisions. Often such systems provide communication amongst stakeholders, help them share data and documents or even provide models for the decisions. But, the decision-making itself in many of these methods reduces to "the magic occurs here."

However, there are two classes of technologies that address the “magic”: Decision Relationship Management and Decision Analysis Systems.

Decision Relationship Management

Rittel (Rittel 1973) describes Issue-Based Information Systems (IBIS), a model for organizing the deliberation process that occurs during complex decision-making. The IBIS model organizes the deliberation process into a network of three data elements, *Issues, Positions,* and *Arguments.* IBIS is a directed graph, a structured form of mind mapping. Over the years, IBIS has been refined and has spawned many systems that attempt to capture the relationships among the decision information. Two recent efforts specifically designed for the development of technical systems are the Decision Breakdown Structure (DBS) (Kam 2005) developed to support decision-making in architecture and DRed (Design Rationale Editor) a joint effort between Cambridge University and Rolls Royce (Bracewell 2009).

DRed began in 2002 and originally developed to support the capture of design rationale, has progressively evolved into a tool to map an information space covering product planning, specification and service. It has seen steady increase in use and part of the PLM toolkit across Rolls Royce. As a design rationale tool, it has four main applications, namely:

- Designing a solution (solution synthesis).
- Capturing the final design and its rationale.
- Diagnosing a problem (problem understanding).
- Completing a standard checklist template.

As an example of solution synthesis, Figure 8 shows part of DRed for the problem “How to prevent the perforate skin debonding from the honeycomb?” (top center). Four alternative functional reasoning paths descend from this issue. Each path shows the logic used to explore alternative solutions to the problem so the best can be chosen. Colors are used to denote the status of the node and symbols for its acceptance or rejection.

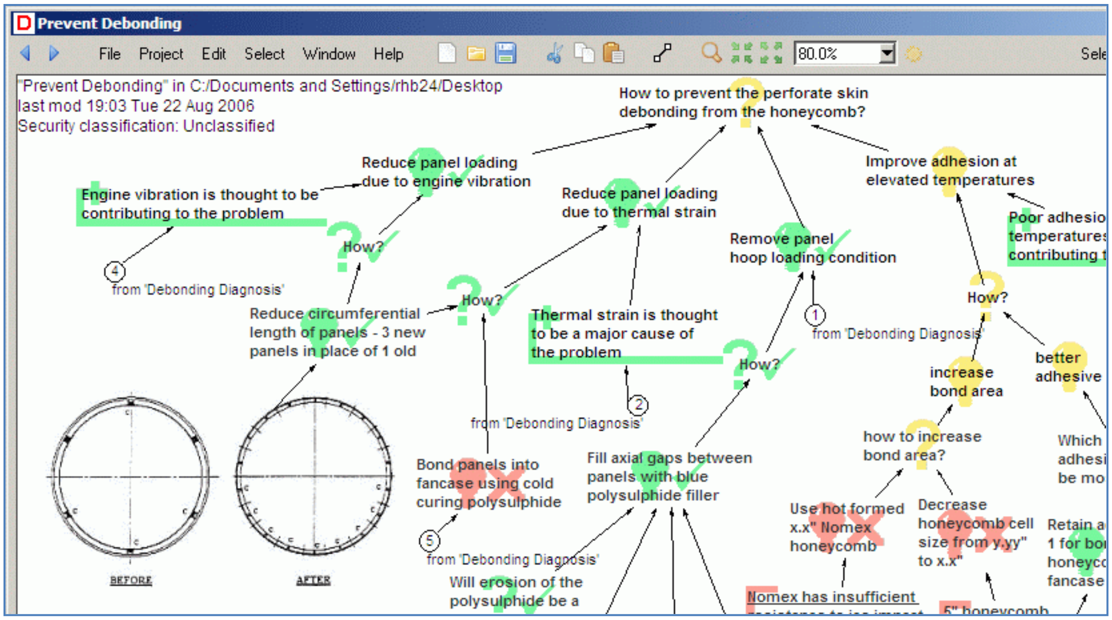

Figure 8: DRed example, partial map for "Prevent Debonding"

In an exploratory study (Eng 2011), interviews revealed positive opinions of DRed's impact in areas including creativity, communication, rationale capture, and organizational learning. Methods like DBS and DRed have not yet been widely adopted, although their acceptance is increasing.

> Implication for PLM:
> Decision Relationship Management systems may find a home in PLM to help in organizing the creation and query of decision information.

Decision Analysis Systems

Decision Analysis Systems are designed to help the decision makers determine the alternative satisfaction for structured decisions by 1) organizing the evaluation of the alternatives relative to the criteria, 2) providing analysis for actually calculating alternative satisfaction and 3) capturing the rationale for decisions. The simplest example of this class of tool is the decision matrix, aka Pugh's method (Ullman 2010, 221-226). It is simple to use and has proven effective for comparing alternative concepts. The basic form for the method, the Decision Matrix, is shown in Figure 9 for the selection of a vendor.

The method provides a means of scoring each alternative concept in its ability to meet a set of criteria. Comparison of the

			Alternatives		
		Wt.	Vendor 1	Vendor 2	Vendor 3
Criteria	Low cost	.3	4	4	4
	Fast response time	.17	3	3	5
	Fast training time	.17	2	4	5
	Easy to use	.17	1	4	4
	Strong team	.1	3	4	2
	High team experience	.1	3	4	2
	Weighted total	1.0	2.8	3.8	3.9

Figure 9. A common Decision Matrix

scores developed then gives insight to the best alternatives and useful information for making decisions. Limitations of the decision matrix are (from (Ullman 2006) with additions):

- Not supported by any theory or analytical methodology. The final score is just a proxy for satisfaction.
- Can't include uncertainty – you must abstract all alternatives to the same level of abstraction.
- Can't manage incomplete information – you have to evaluate against all the criteria regardless of whether or not you know anything about it.
- Difficult to mix qualitative and quantitative evaluation results. Where some of the features may be evaluated qualitatively and others the result of simulations and analysis, there is no way to fuse these results and all must be reduced to qualitative evaluations.
- Can't fuse different team member's evaluations
- Gives limited indication about what to do next to reach a decision.
- No clear rationale for the decision captured (Haymaker 2006)

One method to overcome these limitations is to combine Bayesian methods with the Decision Matrix. Traditionally, Bayesian methods have been used to model uncertain systems, detect spam, and decode ciphers amongst other uses (McGrayne 2011). Here, Bayesian methods give a firm underlying mathematics that supports uncertainty, can manage incomplete information, can combine qualitative assessments with quantitative, can fuse team member evaluations and provide what-to-do-next analysis as part of a clear rationale.

Using Bayesian methods, each cell on the decision matrix in Figure 9 represents the probability that the alternative meets the criteria. Initially all the probabilities are .5 or 50% implying that the evaluation is unsure, no better than the flip of a coin. Thus, the weighted total satisfaction for each alternative is also initially 0.5 or 50% (as the weights are normalized to total 1.0). As assessments are made, the 0.5 values are updated using Bayes rule. This way, if no assessment is made – the information is incomplete - the value remains at 0.5.

If the criterion is qualitative (e.g. "strong team" in the example in Figure 9) then the evaluation is in terms of Yes or No. But, in reality, people modify their responses to Boolean type questions in two ways. First, some teams are stronger than others so there is an amount of "yesness" in assessing the vendor teams. Second, there is a level of certainty or knowledge on which the assessment is based. It may be that the vendor is well known to the evaluator (high knowledge or certainty) or that the assessment is made on only the information in the submitted bid (low knowledge or certainty). The mathematics to take into account qualitative evaluation yesness and certainty using Bayesian methods have been developed (see Appendix A in Ullman 2006a).

Similarly, quantitative assessment can be probability based. For these, there are two considerations that are important. First, quantitative measures have a target value. For example, a target for "fast response time" might be 500msec and this target might be what is stated in the request for proposals. But, say that three vendors meet this specification and to varying degrees meet all the other criteria. But another vendor just misses this requirement at 510msec, but is very strong in meeting all the other criteria. This vendor may be the best choice. What if they could only provide 550msec, or 600msec response times? At what point are they no longer a viable option in spite of their other strengths? Thus, it is important to not only worry about the target, but also a threshold. In the example, the threshold may be 600msec or some other value depending on the needs of the system. The target and the threshold together define the goal for a fast response time.

Secondly, the actual ability of a vendor to meet the criteria will be uncertain. If the bid is based on a system that only exists on paper, then a vendor's estimate of 500msec may have a variance of 100msec or more. If the system exists and has been tested, then there is still some variance in the response time due to noise and other uncertainties.

It is the mathematical combination of the target and threshold on one hand (i.e. a utility function) with the estimate and its variance, which gives the probability that the alternative will meet the criterion. Note that, even though the analysis is in terms of probabilities, the evaluation information is in terms of the units of measure. This handling of quantitative information as probabilities of successes is also detailed in Appendix A of Ullman 2006a.

Often, during the evaluation of alternatives there are inconsistent results. Where one evaluator thinks the team is strong another may not see it the same way. Where one evaluation of the response time yields one result, another model or source of information may not agree. Bayesian updating allows for the combination or fusion of inconsistent evaluations and provides measures for team evaluation consensus. If consensus is high then there is strong confidence in the evaluation. If it is low, then maybe this inconsistency should be resolved, may be not. Guidance on whether or not to resolve low consensus is also possible through Bayesian analysis.

Bayesian methods allow the calculation of the Value of Information (VIO). This analysis identifies which cells in the decision matrix should be refined with additional effort. In other words, it identifies which evaluations, if refined could change the satisfactions values significantly. This is an automation of the what-to-do logic in Figure 7. This analysis helps build the rationale (not just record it) by guiding the evaluation of alternatives, the evaluation of them and the selection of the best one.

One product that enables a Bayesian approach to the Decision Matrix is the *Accord*™ software introduced in 2002 (see www.robustdecisions.com for details on *Accord*).

> Implication for PLM:
> Decision Analysis Systems should be a part of PLM to help in supporting the team while making structured decisions and developing the design rationale.

6. Impact of decision thinking on PLM

This paper began with "Design is the evolution of information punctuated by decisions". Where information capture and query are well developed in PLM, decision-centric thinking is just beginning to evolve. We have explored the types of information that are needed to support this decision-centric view of the product lifecycle. From this development we have identified 13 implications for PLM. A majority of these are predicated on current areas of design process failure or limitation. It is clear that through the use of PLM systems many of these can be relieved. Current PLM systems do an excellent job in supporting some of the implications. For others, this paper points the way to enhanced PLM information management and decision support.

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References

(ARM 2008) J. Hojlo, M. D-Aquila, K Carter, The Product Lifecycle Management Market Sizing Report, 2007–2012, ARM Research http://www.plm.automation.siemens.com/en_us/Images/AMR%20-%20The%20Product%20Lifecycle%20Management%20Market%20Sizing%20Report%2020072012%2008-07-16_tcm1023-67669.pdf

(Bracewell 2009) R. Bracewell, K. Wallace, M. Moss, D. Knott, *Capturing Design Rationale*, Computer-Aided Design, No 41, (2009), pp 173-186.

(Chmielewski 2009) A. Chmielewski, and C. Garner How to Calculate Budget Reserve for Your Project, 6th NASA Project Management Challenge, Feb 2009. Also, personal communication between Dr. Chmielewski of JPL and Dr. David Ullman.

(Golovatchev 2007) J. D. Golovatchev O. Budde, Next Generation PLM - an integrated approach for the Product Lifecycle Management Proceedings of ICCPR2007: International Conference on Comprehensive Product Realization 2007, June 18-20, 2007, Beijing, China

(Cooper 1998) R. Cooper et al, Portfolio Management for New Products, Addison Wesley, 1998

(Dylla 1991) N. Dylla, *Thinking Methods and Procedures in Mechanical Design*, Dissertation, Technical University of Munich, 1991, in German. Data reduced from dissertation in (Ullman 2006a) pp 125-126, 143.

(Eng 2011) N. Eng, M. Aurisicchio, R. Bracewell, and G. Armstrong, *More Space to Think: Eight Years of Visual Support for Rationale Capture, Creativity, and Organizational Learning in Aerospace Engineering*, Accepted to the 2011 Design Engineering and Technical Conferences & Computers and Information in Engineering Conference.

(GAO 2009) United States Government Accountability Office (GAO), Defense Acquisitions, *Many Analyses of Alternatives Have Not Provided a Robust Assessment of Weapon System Options*, GAO-09-665, 2009.

(Gladwell 2005) M. Gladwell *Blink*, 2005, Little Brown, 2005.

(Gigerenzer 2007) G. Gigerenzer, *Gut Feelings*, the intelligence of the unconscious, Viking Adult, 2007,

(GSA 2007) United States General Services Administration, IT *Budget Submission Instructions: Guide for Major IT Initiatives (BY2009 Exhibit 300 & Exhibit 53)*. Washington, DC: Office of the Chief Information Officer, 2007, http://colab.cim3.net/file/work/CPIC/GSA%20BY09%20for%20IT%20Majors_7.11_v3.1.doc.

(Haymaker 2006) Haymaker, J, et al, Managing and Communicating Information on the Stanford Living Laboratory Feasibility Study, Center for Integrated Facility Engineering, Civil and Environmental Engineering, Stanford University, 2006

(Howard 1966) R.A. Howard, Decision Analysis: Applied Decision Theory, Proceedings of the 4th International Conference on Operational Research, 1966, pp. 55–77. http://decision.stanford.edu/library/ronald-a.-howard/Decision%20Analysis-%20Applied%20Decision%20Theory.pdf/view.

(Kam 2005) C. Kam, *Dynamic Decision Breakdown Structure: Ontology, Methodology, & Framework for Information Management in Support of Decision-Enabling Tasks in the Building Industry*, CIFE Technical Report #164, 2005, Center for Integrated Facility Engineering, Stanford University

(Klein 2004) G. Klein *The Power of Intuition: How to Use Your Gut Feelings to Make Better Decisions at Work*, Crown Business, 2004.

(Kuffner 1991) Kuffner T.A., and D. G. Ullman, The Information Requests of Mechanical Design Engineers, Design Studies, Vol 12, No 1, Jan 1991, pg 42 – 50.

(McGrayne 2011), Sharon B. McGrayne, *The Theory that Would not Die*, Yale Press, 2011.
(Nutt 2002) Paul C. Nutt, *Why Decisions Fail,* Berrett-Koehler Publishers, 2002.
(OMB 2008) United States Office of Management and Budget *Circular No. A–11, Preparation, Submission, And Execution Of The Budget*. Washington, DC: Executive Office of the President, 2008. http://www.whitehouse.gov/sites/default/files/omb/assets/a11_current_year/a_11_2010.pdf
(Plous 1993) S. Plous, *The Psychology of Judgment and Decision Making*, McGraw Hill, 1993.
(Rittel 1973) H.W. Rittel and M.M. Webber, Dilemmas In a General Theory of Planning, Policy Sciences, 4, pp 155-169, 1973.
(Robertson 2009) B.F. Robertson, D.F. Radcliffe, Impact of CAD tools on creative problem solving in engineering design, Computer Aided Design, #41 (2009), pp 136-146
(Savage 1955) L.J. Savage, *Foundations of Statistics*, 1955, 2nd revised edition. Mineola NY: Dover, 1972.
(Standish 2009) Standish Group, *2009 Chaos Report*, https://secure.standishgroup.com/
(Stauffer 1991) L.A. Stauffer and D.G. Ullman, Fundamental Processes of Mechanical Designers Based on Empirical Data, Journal of Engineering Design, Vol 2, No 2, 1991.
(Ullman 1991) Design Histories: Archiving the Evolution of Products, Proceedings of the DARPA Workshop on Manufacturing, Feb 5-6, 1991, Salt Lake City Utah
(Ullman 1994) D.G. Ullman, Issues Critical to the Development of Design History, Design Rationale and Design Intent Systems, ASME Design Theory and Methodology Conference, DTM94, Minneapolis, Sept 1994, pp 249-258.
(Ullman 1998) D.G. Ullman, A Taxonomy of Design Rationale Queries, unpublished.
(Ullman 2001) D.G. Ullman, Robust Decision-Making for Engineering Design, Journal of Engineering Design, Volume 12, Issue 1, 2001, Pages 3 - 13
(Ullman 2005) D.G. Ullman, Personal consulting experience, unpublicized.
(Ullman 2006a) D.G. Ullman, *Making Robust Decisions: Decision Management for Technical, Business, & Service Teams*. Trafford Publishing, 2006. http://www.robustdecisions.com/decision-making-resources/making-robust-decisions-book.php
(Ullman 2006b) D.G. Ullman and B.P. Spiegel, Trade Studies with Uncertain Information, Sixteenth Annual International Symposium of the International Council On Systems Engineering (INCOSE), July 2006.
(Ullman 2009a), D.G. Ullman Decisions Based on Analysis of Alternatives (AoA), EA Journal, January 2009. http://www.robustdecisions.com/AOA.pdf
(Ullman 2009b) D.G. Ullman, Robust Criteria for Robust Decisions http://www.robustdecisions.com/criteriacriteria.pdf
(Ullman 2009c) D.G. Ullman and H. Levine, Five Key Decisions for Portfolio Optimization Pm World Today – Featured Paper –2009. http://www.pmforum.org/library/papers/2009/PDFs/may/Ullman-Levine-PDO-paper.pdf
(Ullman 2010) D.G. Ullman, *The Mechanical Design Process*, 4th edition. New York: McGraw Hill, 2010. http://www.mhprofessional.com/product.php?cat=113&isbn=0072975741
(Ullman 2011) D. G. Ullman and R. Ast, Analysis of Alternatives (AoA) Based Decisions, submitted to Phalanx for review.
(USAF 2008) United States Air Force. *Analysis of Alternative (AoA) Handbook: A practical Guide to Analysis of Alternatives*. Kirtland AFB, NM: Air Force Materiel Command (AFMC's) Office of Aerospace Studies (OAS), 2008. http://www.oas.kirtland.af.mil/AoAHandbook/AoA%20Handbook%20Final.pdf