To be published in the Proceedings of *2002 IEEE Aerospace Conference*, **2002**, *Vol.X, xxx-xxx*

Analysis of the New Millennium Program (NMP) Flight Validation Process Using PTAM

Mark Bergman
Department of Information and Computer Science
University of California, Irvine
Irvine, CA 92612
mbergman@ics.uci.edu

Martin G. Buehler
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
Martin.G.Buehler@jpl.nasa.gov

Abstract – This effort expands on the traditional process analysis that focuses on procedural process as the model for describing complex processes. A new model was developed from observing the New Millennium Program (NMP) process for flight validating new technologies. The new Process Type Analysis Methodology (PTAM) includes four process types, anomaly identification and reflective verification. A number of examples are presented to illustrate the use of the new approach.

TABLE OF CONTENTS

1. INTRODUCTION
2. PROCESS TYPE ANALYSIS METHODOLOGY (PTAM)
3. NMP PTAM/PT (PROCESS TYPING)
4. NMP PTAM/AI (ANOMALY IDENTIFICATION)
5. NMP PTAM/PT (REFLEXIVE VERIFICATION)
6. CONCLUSIONS
7. ACKNOWLEDGEMENTS
8. REFERENCES
9. BIOGRAPHIES

1. INTRODUCTION

Osterweil in 1987 started a revolution in process modeling and analysis with his assertion that process design can be treated like software design [1]. What followed is more than a decade of work on creating *procedural* process software languages and models to be used in implementing business process automation and support systems. The underlying model of a business process was adapted to conform to a procedural view of process definition and execution [2-6]. The term "procedural" is used because its use here is more inline with Osterweil's use of the term in process programming.

Reflective examination of procedural business process programming lead to the question: *Are there other types of processes other than procedural processes?* The question was rooted in the examination of management decision process literature. To start with, in any complex development initiative, we must take seriously Simon's theory of bounded rationality [7-9]. The theory implies that we can never find an optimal, but at most a *satisficing* solution. Accordingly, some business processes could be understood from the view point of heuristics, limited search spaces and the quest for increased *intelligence* and *understanding* during the business process.

This leads to the consideration of business processes as *sensemaking* processes. As per Weick, sensemaking processes are performed when 1) the process goals are ambiguous and need to be defined or 2) the process goals are clear but there is no known prescriptive process that can be performed to satisfy the goals [10]. This implies that we need to consider that not all processes can be performed, or even designed in a procedural fashion. Instead, they often conform to a more open-ended search-and-learn process to obtain desired business outcomes.

The consideration of this view of management decision making lead to modifying the original research question to: *Are sensemaking processes an alternative type to procedural processes?* This, in turn, lead to follow-up questions: *Are processes either procedural or sensemaking? If both exist, how do the two types co-exist?* One way to find an answer to these questions is to observe a complex (i.e. nontrivial) organizational process as it was being performed. The software and system design processes have been studied empirically and theoretically for many years. Field research has been very useful in aligning software process models more closely with empirical observation [11]. Indeed, many important breakthroughs in understanding software and system design processes started from capturing detailed observations about processes used in large, complex projects [11-16].

To answer the research questions, it was considered important that a very structured, complex business process be examined, i.e. one that appears fundamentally procedural on first examination. It is asserted that if in such an environment sensemaking processes were repeatably evident, then this would provide evidence, which supports sensemaking as a second type of organizational work process. It is also asserted that if an extremely structured organizational entity's process shows the use of sensemaking processes, then less structured organizations would likely have them as well.

0-7803-7231-X/01/$10.00/© 2002 IEEE

NASA's New Millennium Program process was selected as an appropriate match to answer the research questions. In short, this field site is a professional program that has a history of doing space flight system validation under very ordered, stringent and exacting conditions. As part of NASA, they are required to have well defined and structured processes [17, 18]. In addition, information about their advanced work in complex system design could be very valuable for other organizations faced with similar tasks and issues.

The New Millennium Program's mission and objectives are (as per their website http://nmp.jpl.nasa.gov/technology/technology.html):

> "To identify crucial technologies required for NASA's future, ambitious missions, technologists are guided by the agency's scientific roadmaps. The New Millennium Program Technologist attempts to match the technical requirements outlined in the roadmaps with technologies emerging from the national "pipeline." This pipeline consists of current technology-development efforts in the private sector, academia, non-profit organizations, and other government and NASA centers."

In addition:

> "The {New Millennium} program is unique, however, since it tests its advanced technologies in space flight. Though many space-related technologies can be tested sufficiently in laboratories on Earth, the technologies and concepts NMP selects, such as solar electric (ion) propulsion or spacecraft flying in formation, present a fairly high risk to missions that will use them for the first time. Flight testing in space is also important for some technologies because spacecraft may encounter environments or situations in space that cannot be replicated on the ground: zero gravity, for instance, or environments with appropriate levels of radiation exposure or solar wind.
>
> ... {Annually,} NMP sends a mission into deep space or into orbit around the Earth to test new suites of technologies."

This paper is organized as follows. In section 2, a process analysis framework is defined and discussed. Section 3 discusses the application of the PTAM process typing method to the NMP process. Section 4 examines the outcomes of employing the PTAM anomaly identification method. Section 5 discusses the application of the PTAM reflexive verification method. Section 6 concludes the paper with a discussion of the implications of the findings and some suggestions for follow-up work.

2. Process Type Analysis Methodology (PTAM)

The goal of the process analysis framework is to be able to apply a consistent framework to an organizational entity in order to reveal hidden and tacit features, to better understand how the organization's processes work, and to identify expected and unexpected outcomes. In so doing, the process analysis framework could provide early warning of potential process problems. Also, it is expected that constructing and applying the framework to the NMP process will provide evidence to answer the aforementioned research questions.

PTAM Background

The observed NMP processes were examined for the factors that best describe and define their processes. This was done to allow for a deeper analysis of the processes by 1) supplying a "grounded" process model that can be used to organize and describe the NMP process [19] and 2) being a basis for further process analysis to determine how "well" the NMP process was doing in performing its mission. During the over four month observation period of the NMP process, the main observed process factors were functional, economic, participatory, and governing framework.

To identify the process types, a table of attributes that a process type would show was constructed based on the implications of the procedural and sensemaking literature. These implications were adapted to the process factors for clearer distinction between the types, as well as providing a method by which to do process typing. The first table is shown in **Table 1**.

Table 1 First Process Node Typology Template

Process Node Factors	**Process Node Type**	
	Procedural	*Sensemaking*
Functional		
Economic		
Participatory		
Governing Framework		

Further examination of the processes revealed another process type factor, namely proactive and reactive. Proactive processes were initiated in a preplanned, or proactive, manner. Reactive process were initiated in response to unexpected events. As such, most reactive processes are known process exceptions. It was argued by in 1997 by Osterweil that reactive processes could exist, since exception handling was also part of software engineering [20, 21]. It is asserted that some of the processes as observed in the NMP process support this claim. This is discussed more fully in the *NMP Process Typing* section.

As a result of these observations, the secondary classification of proactive or reactive was added to the

process types. The resulting four process types are shown in **Table 2**.

and analyzing participants behaviors and motivation allows for deeper understanding of what the process objectives are as well as expected outcomes.

Table 2 Developed Process Node Typology Template

Process Node Factors	**Process Node Type**			
	Procedural		*Sensemaking*	
	Proactive (PP)	*Reactive (PR)*	*Proactive (SP)*	*Reactive (SR)*
Functional				
Economic				
Participatory				
Governing Framework				

Process Node Factors

A process model is a graph based representation of the processes [13]. The graph is composed of process nodes and flows that connect process nodes. The detail of the process is captured mainly in the process nodes. A process node can be an encapsulation of subprocesses. A subprocess is a constructed the same as a process. It is a localized detail of a part or all of a complex activity.

Due to the overall complexity of the NMP process, the whole NMP process model will not be presented in its entirety. Instead, the most salient examples of the application of the process framework to the NMP process are presented (in the section after the process framework definition).

Functional Factors – The functional factor indicates how a process works. More specifically, how the process was organized and executed as well as the necessary inputs, supplementary resources, and expected outputs.

Economic Factors – The economic factor focuses on the resource costs, especially in time and money, in performing a process. It also includes the perceived risk in undertaking a project or utilizing a technology. There were direct observations of system design and development modeling, which utilized the history of previous process cycle execution economic costs as part of the model. When a current process node was completed, the economics of the node were captured (as possible) and added to the history. Also, economic factors are used as the baseline to determine process "efficiency." Altogether, economic costs were considered very important in every process step (i.e. node).

Participatory Factors – To understand how and why a process in constructed and implemented, it is also important to understand to process participants [19]. Since each process can have different people involved, it is best to understand the general roles the people perform to better identify the connection between process and people. These roles are defined in the next section. In addition, observing

All processes must have entities who have a vested interest in having the process node performed. An entity is either a person, a collection of people (i.e. a board), a group or department, or an organization (company, government body, university). Usually it will be an individual, a collection of people or a group. As not to be overly specific, an entity is represented by its role. For example, if the process owner is always the director of information systems (from dept x, in company y), the role (i.e. title) would be used. If desired, actual people's names or pseudonyms can be used in addition to their role. Those in charge of a process must know (i.e., define) what the process objective is and need to be satisfied (using a known, reasonable measure) with how the process is performed. Otherwise, there would be a process failure, regardless of whether the process is performed functionally correct and within economic factors.

Each process has a set of participants that are required to perform a process. As observed in the NMP process, the participants tend to fall into the following process roles[1]:

- Process Owner (PO): One or more entities (e.g. person/people/group/ organization) who pays for and controls the process to be performed.
- Customer: One or more entities which receive the benefit of the process.[2]
- Provider: One or more entities which supply resources, e.g. inputs and supplies, for the process.
- Process Actor: One or more entities who perform the process.
- Supporter: Entities that are used to support the process, while not being a process actor/agent. For example,

[1] The process roles are generalizations of participants' roles as observed in the NMP process. They also roughly correspond to principal-agent theory (principle/process owners, agent/process actors), microeconomics (customers, providers/suppliers) and business process design.

[2] In the NMP process, the customer does not pay for the process to be performed. The PO(s) pay for the process activity.

NMP system architects and review board members can be viewed as NMP process supporters.

There are always at least one principal, customer, supplier and actor per process node. There may be no supporters though. Also, the same entity can assume multiple roles, though that does not tend to happen in NMP. Also, a technology, as necessary, can be a customer, supplier, actor or supporter[3]. For instance, a database can be a supplier of information, a customer of an analysis or an actor executing a process. In general, though, these roles will be filled by individual persons or small groups of people.

Governing Framework – It was observed that all processes had a governing framework that guided the processes' execution. This framework consists mainly of the process objectives, principles, and rules, policies and alike. The process objectives are determined by the process owners. They are the baseline by which process "correctness" is measured. Principles are guiding values by which the process is constructed and run. Some of the preeminent principles of the NMP process are fairness, promoting open competition and the desire to get the best technologies from the best providers. Lastly, rules, policies, and alike, are strict boundaries that are used to define and manage the process.

Process Node Types

The examination of the NMP process revealed different process types. Some processes where very procedural in design and execution. Still, other process nodes were not a program of steps performed in an expected manner. There were processes where getting a desired outcome happened in the absence of a clear procedure, i.e. using sensemaking. Also, some of the processes occurred according to a well planned schedule. Still, other process were only activated in response to unpredictable, yet usually well understood, events. Altogether, this lead to determining and verifying a set of four process types, any of which could be assigned to each process node (process or subprocess) as appropriate.

Procedural – Procedural processes have well, often formally, defined steps or activities, which are to be followed when enacting the process [1, 20]. They usually have well defined process goals or objectives. This type of process, in general, also has predefined, expected inputs and outputs. These inputs and outputs can often be measured quantitatively for quality and economic efficiency (cost, timeliness, risk), which, in turn, reflects on the quality and efficiency of the process itself [13]. Since a procedural process steps are well, usually formally, defined, it is also clear when the process as enacted has exceptions, i.e. actions that are taken which are not following to proscribed steps.

Sensemaking – Sensemaking processes are quite different than procedural processes. Sensemaking processes are performed when 1) the process goals are ambiguous and need to be defined or 2) the process goals are clear but there is no known prescriptive process that can be performed to satisfy the goals [10]. Sensemaking process nodes are usually imprecise in description and indefinite in duration. In application, they are usually an application of known activities or heuristics that often lead to successful process resolution. The inputs to a sensemaking process tend to be consistent per process enactment, but the outcomes can vary. Still, any acceptable outcome must conform to agreed upon process goal(s) or objective(s) as well constraints. To be sure this is occurring, sensemaking process activities need to be managed by a well defined governing framework. The governing framework is the defined rules or equivalent used to determine whether the process is going "out of bounds" or succeeding. Out-of-Bounds means the process is executing outside the boundaries of its support. If this happens, the execution process either must be corrected to continue or it fails.

Sensemaking tends to be either an individual or small group artesian activity or occurs during complex interactions amongst like-wise interested process actors (even if each actor has different objectives) [25]. In general, sensemaking processes occur when there needs to be some required learning or judgment to be able to satisfactorily perform the process within a set of given economic and political constraints, i.e. governing framework [10]. The process owner(s) define and enforce the governing framework.

Proactive – Proactive means the process has been planned out in advance. Also. the time or event that starts the process is known in advance. In general, processes tend to be proactive in design and execution.

Reactive – Reactive means the process is event driven, i.e. activated by a specific event, but events occur at unpredictable times. A process event can be defined as a specific, recognizable action (or inaction) that requires a process response.

Procedural–Sensemaking Process Continuum – Procedural and sensemaking can be seen as opposite ends on a continuum of process execution planning. Procedural is bounded on one extreme by rigid order. Since processes need to be flexible enough to execute in an organizational environment, they are rarely rigidly ordered [20]. Hence, procedural indicates that the process task is well known as is how to perform the task, what resources are used, how much time is needed, the level of risk involved, who participates in the process and the process's governing framework (objectives, principles, rules, etc.). Still, It leaves open some room for interpretation in how to enact the process and possible future enhancement.

Likewise, sensemaking is bounded at the other extreme by chaos, i.e. no planning nor strategy employed in planning or performing a process. In other words, chaos can be

[3] This is in alignment with Actor-Network Theory [22-24].

characterized as random action. Since in chaos there is no order and since process requires some order in task planning, execution or approach, chaos cannot be considered a process type. Sensemaking usually includes cycles of planning, understanding, judging and learning by one or interactions of many process actors. Although the action and interaction in a sensemaking process is complex, it is not chaos [26, 27]. Hence, sensemaking is not chaos, although it may appear chaotic at times.

Proactive – Reactive Process Continuum – Proactive and reactive can also be seen as opposites on a continuum of process predictability. Proactive processes have an expectation of time and event predicatively. It is bounded on the extreme by omniscience, i.e. perfect predictability. Since this is not humanly possible, proactive requires only reasonably inferred predictability, usually by well know theory or highly repeatable practice. Proactive also depended on process participants act on the ability to predict and do the planning necessary such that a process can be executed repeatably, at expected times and events.

Reactive is bounded at the other extreme by complete unpredictability. Not every process event can foreseen. But, some events, usually process exceptions, can be considered beforehand and may even be expected. Hence, unpredictable, yet knowable and expected events can be accounted for by a reactive process.

The Four Process Types – In summary, Procedural–Sensemaking and Proactive–Reactive combine to produce four process types:

- A Procedural–Proactive (PP) process tends to be a formally defined process model, such as a state or petri-net model.
- A Procedural–Reactive (PR) process is event driven. When an event is recognized, (usually) formally defined process steps are then executed. Examples of this are exception handling and interrupt recovery processes.
- A Sensemaking–Proactive (SP) is a planned sensemaking activity. Examples of this are stock markets and doing research (including dissertations).
- Sensemaking–Reactive (SR) process is event driven, like Procedural–Reactive. But, as opposed to procedural, sensemaking reactive means one does not know what action to take upon event activation. Instead, this needs to be "figured out." Due to this, sensemaking–reactive process nodes contain the most risks to successful process resolution, while procedural–proactive nodes contain the least risks to success.

A detailed comparison of the different process node types is presented in **Table 3**.

Combining Process Node Types

Process models are a combination of process nodes. Without going into detail, process nodes are connected by *flows*. Also, a process node can be perceived as a module that is composed of many subprocesses.

Flows – A flow is a connection between process nodes. To start, flows are simple, one directional arrows. In addition, flows may be represented by "network," "bus" or "backplane" connections between process modules (similar to those used on UCI Endeavors [28] and C2 projects [29]). These flows can allow for process (nodes or modules) to be inserted or removed from the overall process, while allowing for (but not guaranteeing) continued overall process integrity. Still, for the sake of clarity and focus, complex flow constructs are not presented nor used in this paper.

Process Modules – A process module, at the lowest level, is a connected graph of process nodes and flows that, together, form either a "higher level" process component (e.g. module) or a whole process. The terms "process module" and "process node" are synonymous. A process module can contain other process components (modules). This allows for the formation of process web, tree and forest structures. A process leaf is a single bottom level process node (i.e. it has no subprocesses).

Any process node type can mixed together in a process module. Also, any process node type can be part of a be a subprocess of the process node/module, i.e. a SP process can have PP subprocesses.

Process Type Analysis Methodology (PTAM) Steps

The purpose of defining process node model is to use it in doing an analysis of the NMP process. The analysis is used to determine what is working well and what unexpected outcomes the process produced. In the case of unexpected outcomes, the process analysis should produce indicators of likely problems that should have further scrutiny.

The PTAM analysis follows three steps: Process Typing (PTAM/PT), Anomaly Findings (PTAM/AF) and Reflexive Verification (PTAM/RV). These steps are to be conducted sequentially:

Process Typing (PTAM/PT) – Process typing is done by applying the following three processes:

1) Capture each process via observation, interview and participation.
2) Apply process type template, using the criteria in **Table 3** as a guide.
3) Type the observed processes.

Table 3 Process Node Typology Template

Process Node Factors	**Process Node Types**			
	Procedural		*Sensemaking*	
	Proactive (PP)	*Reactive (PR)*	*Proactive (SP)*	*Reactive (SR)*
Functional	• Activity starting event or time is defined and known in advance. • Activity, itself, is well defined. • Inputs and outputs are well defined.	• Activity is event activated. Events are unpredictable and can occur at any time. • Activity, itself, once started, is well defined. • Inputs and outputs are usually well defined, but can occasionally be surprising.	• Activity starting event or time is defined and known in advance. • Activity, itself, is not well defined in time, event, nor task. Usually learning-by doing. • Inputs and outputs are uncertain and activity dependent , yet there are desired outcomes.	• Activity is event activated. Events are unpredictable and can occur at any time. • Activity, itself, is not well defined in time, event, nor task. Usually learning-by doing. • Inputs and outputs are uncertain and activity dependent , yet there are desired outcomes.
Economic	• Resource costs and time needed should be highly predictive	• Costs and time should be reasonably predictive.	• Costs and timeframe are poorly to unpredictable, but bound by the governing framework or PO.	• Costs and time are unpredictable, but bound by the governing framework or PO.
Participatory	• All participants (process owner(s), customer(s), provider(s), process actor(s), process supporter(s)) are usually well known before and during the process. They also tend to be non-competitive. • Process support is Usually available as needed. Often pre-arranged by PO or actor.	• Participants are unknown before the starting event, but well know after. • Who is a customer or a provider (supplier) depends on the event. There could, but not necessarily, be competition amongst the customers or the providers. One or more process actors are assigned by PO per event, although assignments may be determined ahead of time. • Process support is usually available as needed, but possibly not in a timely fashion	• Some participants are known before hand, but all are well know after. • Could have a set of competitive PO's. Can, when agreed to, have one PO in charge. There can be a number of competitive customers and providers. Competition, if any, tends to be Market-based. Could be multiple process actors. They can, at times, be competitive or cooperative during the process. • Process support is usually available as needed. When possible, they are pre-arranged by PO(s) or actor(s).	• Participants are unknown before hand, but well know after. • Usually a set of Competitive PO's. Can, when agreed to, have one PO in charge. Who is a customer or a provider (supplier) depends on the event. There could, but not necessarily, be competition amongst the customers or the providers. One or more process actors are assigned by PO per event. • Process support is usually available as needed, but possibly not in a timely fashion.
Governing Framework	• Objectives, principles and rules, and alike, are well known and fixed per process execution.	• Objectives, principles and rules, and alike, are usually well known and fixed per process execution, but occasionally ambiguous.	• Objectives, principles and rules, and alike, need to be well defined, but may be ambiguous, and evolving during process execution. • Process needs to be strongly bounded by a governing framework or PO.	• Objectives, principles and rules, and alike, need to be well defined, but are usually ambiguous, and evolving during process execution. • Process needs to be strongly bounded by a governing framework or PO.

Anomaly Findings (PTAM/AF) – After the process models is captured and the nodes are typed, it is time to find process outcome anomalies. An anomaly is a difference between expected or desired process outputs and observed outcomes.

4) Examine the PP processes outputs for *unexpected* observed outcomes. Compare them to the *expected* outcomes and label them an anomaly.
5) Examine the SP processes outputs for *undesirable* observed outcomes. Compare them to the *desired* outcomes and label them an anomaly.
6) Look for *unexpected processes*, especially unaccounted for reaction based processes. Label any unintended (previously unknown) reactive processes as process anomalies. In addition, analyze a PR process like a PP process (see 4). Analyze SR process like a SP process (see 5).
7) Examine process type combination and cycle effects intra-process and inter-process. Also, examine general process cycles over at least 2 complete process cycles. Look for expected and unexpected outcomes.

These process type analysis steps can be applied in any particular order or combination. For instance, process cycle analysis may lead to insights about a PP or SP process, as well as uncover possible reaction based processes. Similarly, an examination of a PP process may indicate some systemic process anomalies. Still, all of these steps should be performed at some point in the analysis.

Reflective Verification (PTAM/RV) – The final step is to verify the "correctness" of the process model and analysis results.

8) Analysis validity using reflective, self-examination: Process actors (NMP technologists) review and provide feedback about the findings. The process actors determine (individually, and collectively) the correctness of the analysis findings.

All findings, i.e. outcomes of the PTAM analysis, are determined by an examination of the observed outcomes of the process versus the expected outcomes. This comparison is performed differently for each of the process types, to account limitations and expectations of each type. In addition, the analysis findings are verified by reflective, self-examination by the NMP technologists. These results are to be used to better understand and improve the analyzed process, as appropriate.

3. NMP PTAM/PT (PROCESS TYPING)

In general, the NMP process can be seen as a triad of process steps: formulation, implementation and flight/infusion, as shown in Figure 1. Formulation (a.k.a. Selection) mainly focuses on identifying and selection systems and subsystems to space flight validate. Implementation (a.k.a. Maturation) consists of maturing the selected system or subsystem(s), creating validation and mission plans, and designing and creating a space flight system. Flight/Infusion contains the validation flight, data analysis and discussion of the results with the customers and providers.

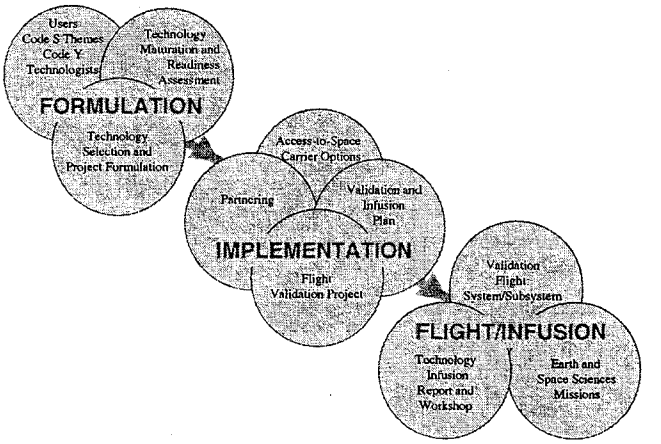

Figure 1 NMP Process Triad

The NMP customers are the science mission themes, within NASA Code S (space science missions) and Code Y (earth science missions). The NMP process owners are NASA administrators who either in charge of the NMP program or the different themes. The NMP suppliers are the providers of technical systems or subsystems candidates for, if selected, space flight validation. The NMP process actors are the NMP technologists who manage and oversee the NMP process. Finally, NMP uses a variety of other supporters from JPL, NASA and external sources as needed.

Due to space limitations, the typing of the whole NMP process cannot be presented. Instead, the exemplar examples of all four types of process nodes are discussed in detail. The following discussion, each of the process node factors found in **Table 3** are illustrated.

All four process types were observed repeatedly in the NMP process. The proactive processes were the easiest to observe. The reactive processes were usually only observable upon process exception (unexpected process event, activity or result). Some reactive processes were determined by "scenario questioning, i.e. "what if" scenarios.

Procedural Proactive: NMP Space Flight Validation Mission

An NMP space flight validation mission itself is a procedural proactive process. There is extensive and detailed planning for every NASA space flight and NMP space flights are no exception. Each step of *functional* activity, from flight system preparation, launch, flight and eventual mission end are procedurally scripted. The timing of each part of the mission plan is well known in advance.

No part of the mission is left to "chance." Contingencies to the plan are included in detail as well, such as "science of opportunity. Hence, the NMP flight project plan also includes procedural reactive processes.

The *economics* of a space flight are modeled and well understood before launch. Although there is often competition as to which space flights become NASA missions, once a space flight mission is accepted by NASA, there is no competition in the execution of the mission. The mission *participants* and their roles are well defined per space flight validation mission. The *governing framework* of a NMP space flight validation is well known. The objectives, principles and rules of the flight are preplanned in detail, and published in a space flight validation plan.

Procedural Reactive: Recovery from Mission Exceptions

A validation plan needs to include recovery from likely mission exceptions, i.e. defined reactive processes to unexpected, yet anticipated, behavior. These procedures include initiating event and *functional* recovery activity. The *economic* costs of doing an error recovery is determined upon exception. Still, each error recovery process creates more economic modeling data that can be used in future plans. The *participants* who deal with an exception are usually determined by the current process actor (person in charge of the current part of the process), and approved by the process owner (usually project manager) as necessary. Still, who is responsible for each system or subsystem is well known in advance. Lastly, a *governing framework* general process objective is to recover from an exception within mission guidelines. Specific error recovery objectives are predetermined in the validation plan. All of these processes are therefore procedural reactive (PR) in type. However, in the case of an unexpected error, the recovery process becomes sensemaking reactive.

Sensemaking Proactive: Concept Determination

To examine a sensemaking proactive process, we switch from space flight validation to the NMP selection process. The selection process starts with the formation of concepts. Concepts are based in the future needs of the science missions as defined by their roadmaps. Concepts are represented by an aggregate list of specific technology requirements. Future science missions are represented by NASA theme technologists and directors. For example, some of the NASA Space Science themes are *Exploration of the Solar System* and *Structure and Evolution of the Universe*. These theme "entities" *participants* are the customers for the NMP process.

The *functional* activity of the process goes as follows. The initial concepts for an NMP space flight are selected by the NMP director and a board of theme directors. The activity by which the concepts are formulated, coalesced and then selected is based in discovery and competition of themes' needs. The output of this process is not predictable, but is *governed* by achieving desired outcomes, i.e. meeting important customer demand in an economically efficient manner. In addition, the selection *participants*, i.e. process owners, cooperate, but also are in competition with one another. The *economic* time and cost of the concept determination procedure is largely unknown until the end of the process. But, once done, the economic costs can be caught for possible future modeling. Lastly, since a new NMP flight process is started once a year, in is known when the concept determination process is to occur.

Sensemaking Reactive: Technology Discovery

There were some observed examples of sensemaking-reactive processes in the NMP process as well. A commonly observed SR *functional* activity during ST7 was a NMP technologist (process actor *participant*) going forth to learn about new technologies that could possibly be candidates for flight validation. The event activation was the discovery, usually via a phone call, email or lunchroom discussion of new, interesting technologies. Once a starting event is recognized, the NMP technologist would set up and conduct an interview with a new technology provider. Over the course of one or more interviewers, the NMP technologist gathers information and then compares it to space flight validation filters. If the technology makes it through all of the filters, then it is recommended to enter the NMP program (if and when it fits a Technology Announcement). The *economics* of doing technology discovery is unpredictable and dependent on the activity followed. The longer and more complex the activity, the higher the cost. The *governing framework* used is mainly the application of the NMP filters to the process.

Process Type Combinations: The SP-PP Cycle from the NMP Technology Selection Process

The subprocesses that underlie the NMP selection process as a whole tend to consist of a string composed of cycling sensemaking proactive (SP) and procedural proactive (PP) processes. The initial formulation and determination of concepts (NMP "Pre-phase A") is a SP process, as previously demonstrated.

The NMP selection process is bounded by the governing framework principles of fairness, open competition, the need to well manage limited resources and the desire to select the best technologies from the best providers. Functionally, in the NMP technology selection process, there are many possible concepts and each concept is 1) somewhat ambiguous in definition at the beginning of the technology selection process and 2) in competition with the other determined concepts. A Technology Announcement (TA) meeting used to officially start the selection process. This meeting is a PP process. Following the TA meeting is gathering, distribution and review of submitted technology proposals. This is a SP process. The submission and review

process tends to be much akin to the review process of academic journals. The results of the reviews are judged by a peer review panel. The review meeting is, in itself, a PP process, while the decisions (recommendations and selections) are made using a SP process. Eventually, the final concept and technology selection is based on a discussion between the process owners, which is grounded in the "open-ended" reviews and recommendations.

The cycling between SP and PP processes was repeatedly observed during the NMP selection process. It gives an indication of how abstract, open-ended aspects of system selection are counterbalanced with managing pragmatic economic factor concerns. Its repeated use demonstrates its resilience and utility in dealing with this difficult trade-off. The SP-PP process bundles are usually augmented with procedural-reactive, PR, processes and occasional sensemaking reactive, SR, processes. The main proactive processes, i.e. technology announcement related meetings and review boards, have some well known processes to deal with exceptions. Some of these reactive processes were seen during the course of ST7 selection process. These include changes in reviewers, board member scheduling problems, and dealing with incomplete proposals. There are likely others, but they only are seen upon event activation.

4. NMP PTAM/AF (ANOMALY FINDINGS)

Once the NMP processes were captured and typed, they were analyzed, using the Anomaly Identification method discussed in section 2. Due to space limitations, only a few of the analysis *findings* are presented in this section. The findings point out the unexpected outcomes of the NMP process. The findings reveal process changes, are instructive as to how the NMP process functions, and reveal process issues likely to require future e attention.

PP Anomaly: Validation versus Science

The NMP space flight validation is a PP process with a number of expected outputs. One *expected output* is that a single space mission can provide both scientific and validation data. This is based on the governing principle of doing science and validation on the same flight mission for economic efficiency reasons. The *unexpected outcome* was contention between gathering science data and validation data. The process anomaly was contention between performing science and validation in a single space mission.

Background – Initially the NMP program was conceived as primarily a validation mission with a science component that was added once the validation mission was in place. The introduction of the science team was purposefully delayed until the validation effort was well under way. In the present NMP process, science themes are considered NMP customers. Their requirements are included into the program at the outset by choosing projects that satisfy the long-range NASA science mission needs. Since the initiation of ST6, the science data gathering component has been removed as an integral part of the NMP and the program has focused on technology validation. This NMP transformation is shown in Figure 2.

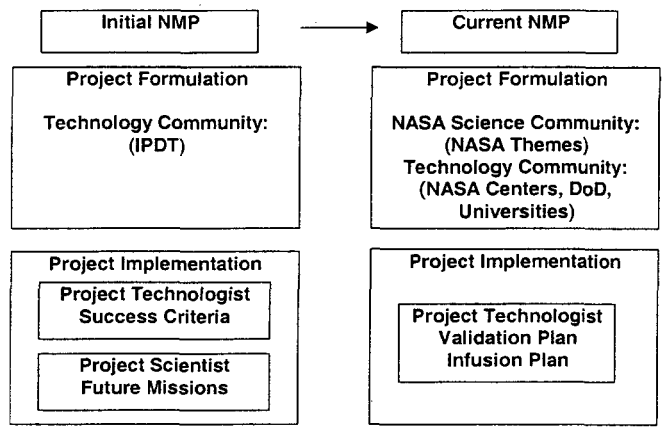

Figure 2 Comparison of the initial and current NMP with respect to the treatment of science.

The requirements of NASA's science community differ from NASA's engineering of technology community in using new technology. Science missions were risk adverse and traditionally used technology that had a well known flight heritage or was low risk. The engineering community always pushed for using the most advanced technology. Because of these diverse needs, NASA decided to focus the NMP on validating new technologies that have the potential of reducing the risk and cost to NASA's Earth and Space Science missions.

As seen in Figure 2, the initial NMP used technologies provided from the IPDTs (Integrated Project Development Teams). During implementation, the project consisted of a project technologist, who was the advocate for the technology providers. The project scientist looked after the needs of the science community and in particular the needs of future science missions.

In the current NMP, the project technologists again had the responsibility of being the advocate for the technology providers. This task is implemented in the validation portion of the project's Technology Validation and Infusion Plan. The result of space flight validation was the infusion of new technologies into future science missions.

Validation vs. Science Anomaly – Science missions require stable, well standardized system or subsystems in a space flight system. These flight systems are full of delicate and sensitive instruments that are used to perform and experiment, measure experimental results as well as take readings of interesting phenomenon and, (where possible) analyze the captured data. The space flight system, as a whole, and in parts, must be stable, reliable and well calibrated, just like any other scientific instrument.

Validation missions expect a certain amount of uncertainty in the system or subsystem(s) in a space flight system, otherwise there would be no need to do validation. The systems and subsystems under test are not expected to be wholly stable, reliable, nor accurate. In fact, much of the validation plan usually revolves around determining how stable, reliable or accurate a new technology is in a actual domain of applicability (for instance, in deep space or on the surface of Mars). Some tests may be volatile, requiring the destruction of one of more copies of the system-under-validation. Also, since these technologies are not yet stable, they can react in unpredictable ways, as discussed in the procedural reactive process example. Hence, a space flight validation system needs to be flexible enough to recover from expected and unexpected errors.

Mixing precisely stable systems with unstable systems was (and is) very risky. The tests needed to do validation may interfere with or possibly ruin precision science systems or subsystems. In addition, it was very costly to do both. Since validation and science systems cannot be reasonably intermingled, any system that had both needed be able to support science stability and validation uncertainty. Although this can be done, as demonstrated by DS1 (esp. testing the ion engines), it was seen that each space system that attempted to do this was usually over budget and late. Some, like ST4, were cancelled altogether.

Another difficulty with mixing science and validation was organizational, i.e. participant, based. It was difficult to know "who is in charge" of the mission, especially for flight planning, contingency planning and data collection. In NASA, science tends to win if there is a contest between science and validation. This is because one of NASA's main objectives is to perform science. Since NMP's main goal was to do validation, it needed to be made clear organizationally that validation would supercede science. As earlier discussed, the way this was accomplished was to remove the science component from NMP space flights.

In summary, it was expected that science and validation could co-exist on the same space flight. Yet. for the aforementioned reasons, it was clear that science and validation did not mix. Hence, the science component was removed and NMP missions are validation only.

SP Anomaly: Long Term Customer Satisfaction

An example of an anomaly that was found in an SP process is the variance between the desired and actual outcomes of the NMP selection process over many complete NMP process cycles. The desired selection process outcome is the fulfillment of NMP customer demand, as represented by the theme "entities" (see "Sensemaking Proactive: Concept Determination"). The undesirable outcome is that it is not predictable as to whether NMP customer demand can be fulfilled.

The NMP selection process was governed by the principles of fairness and open competition. Specifically, the selection process was open to all US based technology providers that had a system or subsystem that met the specifications in a NMP TA (technology announcement). There was to be no bias as to who can enter (industry, universities and government agencies) or how the process was executed. An NMP technologist could only shepherd the selection process, i.e. assist in explaining and promoting the process, but not directly assisting any provider in making proposals, performing technology readiness analysis or doing technology maturation.

The application of fairness and open competition insured that the local sensemaking aspect of the selection process was intact, i.e. the outcome was not predetermined and only the "best" concept(s) and provider(s) should win. Since only one or very few concepts were selected per NMP cycle, a small number of NMP theme customers would eventually have their desired technology flight validated. But, over time, it was not predictable as to which systems or subsystems would be space flight validated and, hence, which concepts would be selected. Selection was based partially on which candidate system or subsystem was the most "ready" (mature) for space flight validation. A candidate technology may be important, but it could lose in selection to another, slightly more "mature" technology.

Altogether, over time and many NMP process cycles, it was possible that a concept and its representative technologies may never be chosen for space flight validation, even if the concept and technology was considered extremely important by the process owners. This anomaly, if unattended, could lead to increasing NMP customer and provider dissatisfaction and a lack of important technology for future NASA science missions. As currently observed within NMP, solar sail and aspects of autonomy technology fit this anomaly.

Process Type Combinations: Inter-Triad Process Timing Issues

The "Triad Process" is the NMP three step process of formation (selection), implementation (maturation), and space flight validation, as previously shown in Figure 1. The expected outcome was that the timing between the three process was predictable. The unexpected outcome was that that the timing between the processes, especially between maturation and flight, was poorly predictable. The process anomaly was the tension between expected predefined process timeframes with the uncertainties in timing of SP processes.

As earlier stated, the selection process was a SP process. Still, it tended to be bounded in time, as defined by its TA. Although it was fairly clear as to when the selection process ended and the maturation process began, one cannot really start planning and architecting the space flight vehicle, itself,

until selection process was complete. This is an example of poorly predictable knowledge affecting the inter-process hand-off between the selection and maturation processes. To deal with this, NMP flight system architects started to do co-parallel designs as the likely selection "winners" became determinable.

Once in the maturation process, it was very difficult to determine when a system will mature, i.e. how long it will take, how much it costs to do and what the final functionality will be. Therefore, this process has been the hardest to predict accurately in time, cost and risk. There could be significant project delays, at least compared to the expected timeframes laid out in a project plan. Such delays had been observed in ST3, ST4, and ST5. In addition, the maturation process timing issue was exasperated if there were multiple subsystems on a flight, such as in ST6. Already, ST6 has had 2 subsystem drop-outs due to maturation problems.

The unpredictability in the implementation and maturation process affects scheduling for space flight missions. Flight mission scheduling was very complex and time sensitive, as previously discussed. There was (and is) a tight window per year as to who, where and when a space flight mission can be performed. Schedule slipping was quite expensive. Hence, the unpredictability of the maturation process can incur a rather large economic penalty during the flight part of the process.

Altogether, the timing and knowledge passing issues indicate the need to re-examine how to best manage the connections between SP-SP and SP-PP processes. Specifically, it is not possible to treat the whole NMP process as a PP process.

5. NMP PTAM/RV (Reflective Verification)

The last step was to bring the results of the anomaly identification to the people who perform the NMP process for verification of correctness. One need not complete this analysis before starting verification. Having reflective feedback to the process typing and then to the early anomaly identification results can induce other useful insights from the process actors (i.e. NMP technologists) as well as refine analysis findings[4]. Still, when the analysis was complete, a final reflective pass by the process actors (and process owners, where possible) was performed. The findings were adjusted for accuracy and verified by general consensus. All findings in section 4 had gone through reflexive verification.

[4] The analysis process can be more seen as a sensemaking proactive process that relies upon procedural proactive and reactive process. Interestingly, this mirrors some of the systemic processes found in the NMP process itself, such as the technology selection process.

6. Conclusions

Examining the NMP process has given some clear answers to the research questions. Sensemaking processes do indeed exist. It was observed that the NMP selection process must be a sensemaking process due to the application of the governing principles of fairness and open competition to their technology and project selection process. Sensemaking processes were seen repeatedly throughout the NMP process.

Indeed, all four process types were observed in the NMP process. Process nodes were combined linearly or in parallel (via process forks and joins) regardless of type. Still, in general, the main NMP process structure is a combination of PP and SP processes, with many PR process "exceptions." SR process, like technology discovery, were created and executed when necessary.

The SP-PP process cycle was an unexpected finding. This process cycle construct appears to support the toggling between the "known" and the "unknown" as one good method to deal with ambiguous decision making situations, especially when they are bounded by economic resource limitations. Seeing if the SP-PP cycle occurs in other organizations with similar trade-off between learning and wise resource management is the subject of future research.

Sensemaking processes cannot be managed like procedural processes. It was observed that sensemaking process did not conform well to quantitative process management. This type of process is not predictable nor well understood. They are used as a matter of necessity, i.e. used only if a procedural process cannot be adequately substituted. This implies most standard management tools and methods will likely work poorly in sensemaking processes. Instead, sensemaking processes should be governed to find desirable outcomes, while promoting and supporting the "open-ended" activities used to perform the process. Altogether, this indicates the need to further study how sensemaking processes should be managed and better supported for doing complex projects in highly structured organizational environments.

In addition, the demonstrated existence of four process types should start a re-examination of current process modeling languages and tools. This aligns with Lehman's call for process modeling to align more closely with actual, relevant business processes [30]. Most process modeling tools and languages focus mainly on procedural proactive processes [3, 5], with a few including procedural reactive processes [6, 21]. Although sensemaking models do not conform to procedural process models, it should be noted that sensemaking process models may be amenable to complexity theory based agent modeling [25, 31-33]. In addition, new open-ended process architectures will likely be necessary in accommodating the needs of all four process types [29]. Altogether, this opens up some new, interesting areas for further development in process modeling systems.

The NMP process is an evolving organizational process [34], but it is bound tightly be NASA rules and guidelines, i.e. NASA's governing framework. All processes are subject to process improvement via acquired and reflectively examined experience. As demonstrated in this paper, the process analysis framework is a tool which can be used to assist in promoting and performing process evolution.

7. ACKNOWLEDGEMENTS

The authors want to thank the following New Millennium Program technologists who contributed to this effort. They include: Tosh Fujita, Charles Minning, and Abdullah Aljabri. File: Aero1C15.doc

8. REFERENCES

[1] L. J. Osterweil, "Software Processes are Software Too," presented at International Conference on Software Engineering, Monterey, CA, 1987.

[2] B. Scholz-Reiter and E. Stickel, *Business Process Modelling*. Berlin ; New York: Springer, 1996.

[3] A. Finkelstein, J. Kramer, and B. Nuseibeh, *Software Process Modelling and Technology*. Taunton, Somerset, England: Research Studies Press, 1994.

[4] W. H. Kleppinger, D. Y. Tamanaha, and L. J. Osterweil, *The uses of process modeling : a framework for understanding modeling formalisms*. Irvine: Information and Computer Science University of California Irvine, 1992.

[5] G. A. Bolcer, "Flexible and customizable workflow execution on the WWW," 1998, pp. xvi, 237 leaves.

[6] A. G. Cass, B. S. Lerner, S. M. Sutton, E. K. McCall, A. Wise, and L. J. Osterweil, "Little-JIL/Juliette: a process definition language and interpreter," presented at 22nd International Conference on Software Engineering, Limerick, Ireland, 2000.

[7] H. A. Simon, "Rational Decision Making in Business Organizations," *American Economic Review*, vol. 69, pp. 493-513, 1979.

[8] H. A. Simon, *Models of Bounded Rationality*, vol. 2. Cambridge, MA: MIT Press, 1982.

[9] H. A. Simon, *The sciences of the artificial*, 3rd ed. Cambridge, Mass.: MIT Press, 1996.

[10] K. E. Weick, *Sensemaking in organizations*. Thousand Oaks: Sage Publications, 1995.

[11] B. Curtis, H. Krasner, and N. Iscoe, "A field study of the software design process for large systems," *Communications of the ACM*, vol. 31, pp. 1268 - 1287, 1988.

[12] F. P. Brooks, *The mythical man-month: essays on software engineering*, Anniversary ed. Reading, Mass.: Addison-Wesley Pub. Co., 1995.

[13] W. S. Humphrey, *Managing the software process*, Repr. with corrections. ed. Reading, Mass.: Addison-Wesley, 1990.

[14] M. Maier and E. Rechtin, *The Art of Systems Architecting*, 2nd ed. Boca Raton: CRC Press, 2000.

[15] B. W. Boehm, "A spiral model of software development and enhancement," *Computer*, vol. May, pp. 61-72, 1988.

[16] B. Boehm, "Anchoring the Software Process," *IEEE Software*, vol. 13, pp. 73-82, 1996.

[17] "NPG 7120.5A; NASA Procedures and Guidelines: NASA Program and Project Management Processes and Requirements," (http://nodis.hq.nasa.gov/Library/Directives/NASA-WIDE/MSWord_Docs/N_PG_7120_005A_.doc), NASA 1998.

[18] F. K. Li, "New Millennium Program Plan," NASA, JPL, Pasadena, CA 2000.

[19] A. L. Strauss and J. M. Corbin, *Basics of qualitative research: techniques and procedures for developing grounded theory*, 2nd ed. Thousand Oaks: Sage Publications, 1998.

[20] L. J. Osterweil, "Software processes are software too, revisited," presented at ICSE '97, Bostone, MA, 1997.

[21] S. M. Sutton and L. J. Osterweil, "The design of a next-generation process language," presented at Foundations of Software Engineering, Zurich, Switzerland, 1997.

[22] W. Bijker and J. Law, "Shaping technology / building society: studies in sociotechnical change." Cambridge Ma: The MIT Press, 1994.

[23] B. Latour, "Social theory and the study of computerized work sites," in *Information technology and changes in organizational work*, W. J. Orlikowski, G. Walsham, M. R. Jones, and J. I. DeGross, Eds. London: Chapman & Hall, 1996, pp. 295-307.

[24] G. Walsham, "Actor-Network Theory and IS research: Current status and future prospects," in *Information systems and qualitative research*, A. S. Lee, J. Liebenau, and J. I. DeGross, Eds. London: Chapman and Hall, 1997, pp. 466-480.

[25] R. M. Axelrod and M. D. Cohen, *Harnessing complexity: organizational implications of a scientific frontier*. New York: Free Press, 1999.

[26] P. Cilliers, *Complexity and postmodernism: understanding complex systems*. London ; New York: Routledge, 1998.

[27] P. Cilliers, "What Can We Learn From A Theory of Complexity," *Emergence*, vol. 2, pp. 23-33, 2000.

[28] "Process Research And Endeavors," (http://www.ics.uci.edu/pub/endeavors/endeavors.html), University of California, Irvine, 1999.

[29] "Software Architecture Research," (http://www.ics.uci.edu/pub/arch/), University of California, Irvine, 1999.

[30] M. M. Lehman, "Process Modelling -- Where

next?," presented at ICSE '97, Boston, MA, 1997.

[31] J. H. Holland, *Hidden order : how adaptation builds complexity*. Reading, Mass.: Addison-Wesley, 1995.

[32] R. M. Axelrod, *The complexity of cooperation : agent-based models of competition and collaboration*. Princeton, N.J.: Princeton University Press, 1997.

[33] K. Miettinen, *Evolutionary algorithms in engineering and computer science : recent advances in genetic algorithms, evolution strategies, evolutionary programming, genetic programming, and industrial applications*. Chichester ; New York: Wiley, 1999.

[34] D. P. Truex, R. Baskerville, and H. Klein, "Growing systems in emergent organizations," *Communications of the ACM*, vol. 42, pp. 117 - 123, 1999.

9. BIOGRAPHIES

Mark Bergman is a doctoral student in the Computing, Organizations, Policy, and Society (CORPS) program in the Department of Information and Computer Science (ICS), University of California, Irvine (UCI). His research interests are in the areas of systems design lifecycle processes, especially in the areas of requirements analysis, process modeling, verification, validation and infusion; computer supported cooperative work (CSCW) and organizational-technical strategy formulation. He has a B.S. from the University of California, Berkeley in EECS (Electrical Engineering and Computer Science), awarded on 3/83, and a M.S. from the University of California, Irvine in Information and Computer Science, awarded on 6/97. He has worked for over 10 years in Silicon Valley (Cupertino and Mountain View, CA) companies in between getting his B.S. and M.S. He has worked at Hewlett-Packard, Sun Microsystems, and Tandem Computers in a variety of roles, including: software engineer, quality assurance engineer, first line project manager and consultant. He is a member in good standing of the following professional organizations: ACM, AOM, ASQ, IEEE, INCOSE, INFORMS and SMS.

Martin G. Buehler received the BSEE and MSEE from Duke University in 1961 and 1963, respectively and the Ph.D. in EE from Stanford University in 1966 specializing in Solid State Electronics. He worked at Texas Instruments for six years, at National Bureau of Standards (now NIST) for eight years, and since 1981 has been at the Jet Propulsion Laboratory where he is a senior research scientist. At JPL he has developed p-FET radiation monitors for CRRES, Clementine, TELSTAR and STRV, E-nose which flew on STS-95, and an electrometer for the Mars '01 robot arm. Currently he serves on the staff of the New Millennium Program as a technical analyst. Martin is a member of the IEEE, Tau Beta Pi, and Sigma Nu. He holds 12 patents and has published over one hundred papers.