

VALUE STREAM ANALYSIS AND MAPPING FOR PRODUCT DEVELOPMENT

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Abstract

This paper explores the concept of Value Stream Analysis and Mapping (VSA/M) as applied to Product Development (PD) efforts. Value Stream Analysis and Mapping is a method of business process improvement. The application of VSA/M began in the manufacturing community. PD efforts provide a different setting for the use of VSA/M. Site visits were made to nine major U.S. aerospace organizations. Interviews, discussions, and participatory events were used to gather data on (1) the sophistication of the tools used in PD process improvement efforts, (2) the lean context of the use of the tools, and (3) success of the efforts.

It was found that all three factors were strongly correlated, suggesting success depends on both good tools and lean context. Finally, a general VSA/M method for PD activities is proposed. The method uses modified process mapping tools to analyze and improve process.

1 Introduction

Value Stream Analysis (VSA) is a method by which lean principles are applied in the examination of business processes. In the context of this paper, VSA can be defined as *a method by which managers and engineers seek to increase the understanding of their company's development efforts for the sake of improving such efforts.* The method centers on the metaphor of development tasks which add

value to a final product, efficiently linked together to form a continuously flowing stream of value.

Value Stream Mapping (VSM) is a tool to support its associated analysis. VSM thus can be simply stated as *the method by which the outcomes of Value Stream Analysis are depicted or illustrated.* The VSM of a process serves to describe a highly complex real system in a less complex 2-D format. This simplification of the system facilitates insight and understanding, and provides a common language for communication of that insight.

VSA/M has shown early promise as a method for rapid and low-cost improvement of PD processes. Many legacy processes are burdened with an accumulation of special cases, quick fixes, and extra reviews, which were valuable at some point but have become "monuments" that needlessly slow current work [1]. The result is that the value-added time of many development efforts is as low as 5% of the total cycle time [2]. Although there is some wasted effort in the non-value added time, most of this time is spent in task idle time (i.e. no one is working the task) [3]. Early implementations of VSA/M methods to PD efforts have aided in reducing this wasted time by 50-90% [4].

This paper explores the use of VSA/M methods in aerospace PD. A brief review of lean concepts is followed by the results of a study undertaken by the Massachusetts Institute of Technology's Lean Aerospace Initiative (MIT LAI). VSA/M practices in the US aerospace industry were surveyed. The tools in current use are summarized. The use of various tools is then correlated with both the success of

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the efforts in which they were used, and the lean context (the levels of lean awareness, training, leadership support, etc.) in which they were used. The paper ends with a summary of a suggested method for PD VSA/M that is more fully explored in reference [5].

2 Background

Lean theory originated in the practices of the Toyota Motor Corporation, codified and popularized through publications such as *The Machine That Changed the World* and *Lean Thinking* [6,7]. These writings focus mainly on the manufacturing aspect of business rather than the engineering and design processes, but maintain that the same principles can be applied to both shop floor and non-shop floor activities. The lessons of Toyota for product development have been captured by Fujimoto and Clark [8] and Ward and Sobek [9].

As categorized by Womack and Jones, the main tenets of lean are:

- Value: providing the customer with the right product, for the right price, at the right time
- Value Stream: the set of actions that bring a product from concept to realization, order to delivery, or raw material to finished good
- Flow: seamless movement through value-creating steps
- Pull: acting only to satisfy customer needs, rather than forcing, or pushing, a product upon the marketplace
- Perfection: continuously and relentlessly improving the value, value stream, flow, and pull in business operations

2.1 Value stream concepts

The value stream is analyzed and mapped in order to reduce the waste in processes, enable flow, and move the process towards the ideal of rapid response to customer pull. In the product development context, this means rapid response to customer needs for both new products and modifications and adaptations of existing ones. The concept of customer pull is particularly

timely in the US military aerospace industry, where major emphasis is being placed on acquisition reform to achieve quick response to rapidly changing warfighter needs.

To date, most value stream mapping work has been done in the manufacturing context. The reference work is *Learning To See* [10], which provides general methods for the practical implementation of VSA/M in manufacturing operations.

The fundamental principle of the method is mapping the current state of a process and applying lean techniques to create an improved future state vision of the process. To develop this future state, non-value-added tasks are identified. These are activities deemed to only support the true value-added tasks (Type I waste – often tasks such as set-ups, reviews, etc.), or that are completely unnecessary in themselves (Type II waste – often “non-tasks” such as waiting in inventory) [7]. A set of techniques are then applied to create a future state vision. In the lean manufacturing context, these include manufacturing cells, just-in-time delivery, parts supermarkets, kitting, etc. The future state map drives an implementation plan. This improved state is then used to generate further future states, and (ideally) the process is continuously improved.

Standard terminology, symbols, and improvement methods allows VSM to be used as a communication tool for both internal communication and sharing techniques and results with the larger lean community. Companies such as Toyota, Pratt & Whitney, Sikorsky, Delphi, Ford, and many others companies have achieved large savings by implementation of Lean principles in their manufacturing activities [11].

2.2 Lean product development

The product development team at MIT’s Lean Aerospace Initiative was launched in 1994 with funding from the U.S. Air Force and aerospace industry companies. The team, whose members represent military, industry, and academic interests, was tasked to apply lean to aerospace engineering and design efforts.

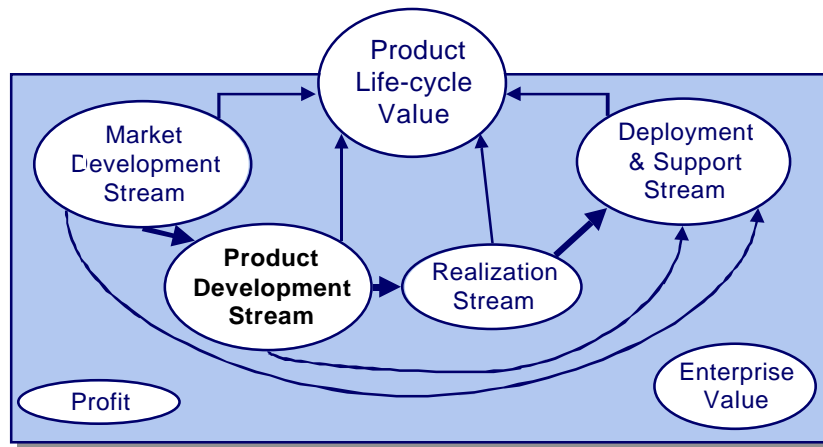


Figure 1. PD Value Context

Early work focused on applying modern tools (e.g. software factory) and organization (e.g. IPTs) to aerospace product development. Since 1998, the team has re-focused on applying fundamental lean principles to the improvement of product development processes. Fundamental questions such as “what is lean value in a PD context?” and “what flows in a PD value stream?” have been addressed both by the team (in a series of workshops [12]) and by individual researchers. The difficulty facing the team is illustrated by Figure 1, which shows the PD value stream deeply imbedded in an enterprise with many functions, which cumulatively provide customer value, as well as serve other stakeholders such as the shareholders (expecting profit) and employees (expecting good jobs, preservation of the enterprise core competencies, etc.).

The team proposed that the **value** of the PD process is “a capability delivered at the right time, for the right price, as defined by the end user.” This value is embodied in an effective and usable product design or “build to” package. This is recognized as something of an idealization, as there is no one clean handoff to manufacturing in a real enterprise (nor should there be!). This notional design package must come about by way of the PD **value stream**, in like manner to the manufacturing value stream, and must then fit in sequence with other

activities in the business cycle, to create some overall value as shown in Figure 1.

Further understanding can be accomplished by breaking the PD process down into stages (see, for example, [13]), and defining their inputs, outputs, constraints, and enablers. This exercise begins to address the **flow** through the PD process. The team took an important step with the consensus that it is **information** that flows through the PD process, just as physical material flows through the manufacturing process. The team characterized the quality of the information flow in terms of Form, Fit, Function, and Timeliness (FFFT). Value within PD develops not only as a function of the FFFT of the information included within the design package, but also as a function of how well that design package allows the final product to meet the FFFT desires of the customer. Further work on the definition and understanding of value in product development has been done by Chase [14] and Slack [15].

As the information flows and matures through this process, the tasks performed add value to the information, transforming it from its initial state of raw data to the completed build to package. However, not everything that begins as raw data results in useful information, and the team recognized this through the application of the seven manufacturing waste categories to information, listed in Table 1.

Table 1. PD Information Wastes

| | Waste | Description |
|---|----------------------|---|
| 1 | Overproduction | too much detail, unnecessary information, redundant development, over-dissemination, pushing rather than pulling data |
| 2 | Transportation | information incompatibility, communication failure, multiple sources, security issues |
| 3 | Waiting | information created too early or unavailable, late delivery, suspect quality |
| 4 | Processing | unnecessary serial effort, too many iterations, unnecessary data conversions, excessive verification, unclear criteria |
| 5 | Inventory | too much information, poor configuration management, complicated retrieval |
| 6 | Unnecessary Movement | required manual intervention, lack of direct access, information pushed to wrong sources, reformatting |
| 7 | Defective Product | lacking quality, conversion errors, and incomplete, ambiguous, or inaccurate information, lacking required tests/verification |

3 Research Design

Visits were made to nine major U.S. aerospace development sites to determine the current practices and maturity of VSA/M within the industry. These visits took place from January to August 2000. The research methodology involved collection of data by several means, including interviews, participatory research, workshops, presentations, and both formal and informal discussions concerning the topic. Each of the nine sites was engaged in a PD process improvement effort. A total of 31 interviews were conducted; and a total of 48 subjects participated in the study. The data collection focused on the three themes:

- The process mapping and VSA/M tools used at each of the sites
- The context surrounding their use
- The self-assessed success of the respective process improvement efforts

The collected data was reduced as follows. The various methods used were evaluated for their ability to describe process characteristics, including:

- Time: concurrency, task duration, and start/stop times
- Work: decision branching, feedback, flow, inputs/outputs, iteration, metrics, task precedence, resources, tasks, and value
- Structure: geography, grouping/teaming, milestones, and organizations

The evaluations were summarized as ratings of the ability of a method to 1) represent a process, and 2) assist in the analysis of the process for

improvement. Both the basic methods, and the methods as used at the study sites (which were usually modified) were rated in this way.

The context information was reduced to a rating of “lean context” by considering the following factors:

- Opportunity for lean education and training
- General resource allocation for business improvement efforts
- Leadership involvement in business improvement efforts
- Organizational integration of lean principles
- Lean vision or goal

4 Results

4.1 Available tools

A number of existing process analysis tools will be briefly reviewed here, some of which were not originally intended for use in the mapping of a value stream. This list is not intended to be exhaustive, but rather reflects the tools actually found in use in the U.S. aerospace industry.

4.1.1 Gantt chart

The venerable Gantt chart is a traditional method for displaying sequence, schedule, and dependency between tasks. It is widely used in the PD community for display of schedule and milestone information.

4.1.2 Ward/LEI map

Alan Ward of Ward Synthesis, Inc, has advanced a map that highlights the concurrent

and cyclic nature of PD processes. The map shows time along the horizontal axis, and the magnitude of resources required to perform each task on the vertical axis. Overlapping curves are used to illustrate the time and resources required for each activity.

4.1.3 Process flow map

The application of lean ideas using traditional process mapping tools has also been developed through works such as Trischler's *Understanding and Applying Value-Added Assessment* [16]. These developments use process maps to highlight waste and areas for improvement. Standard symbols are connected by arrows to describe flow, and color can be utilized to denote value-added versus non-value-added assessment.

4.1.4 Learning to see

Rother and Shook's *Learning To See* [10] method, based on factory floor mapping, can be adapted to PD processes once an understanding of how lean concepts, like flow and waste, translate to PD activities. *Learning To See* provides the most proven tool for lean-based VSA/M to date.

4.1.5 System dynamics

Although not a VSM method, *per se*, system dynamics modeling (see, for example, [17]) can be accomplished in the context of a lean improvement exercise.

4.1.6 Design structure matrix (DSM)

The DSM technique is a well-developed method for analyzing the sequences of, and information flows between, the tasks in a process. An "n-squared" matrix is used to depict the information flows from one task to another. The matrix can be numerically optimized to minimize iterations and maximize the potential for concurrent work. A complete description of the method, with tutorials for its use, can be found at the MIT-DSM website [18]. A sophisticated extension of this technique can also be found in reference [19].

4.2 Evaluations

The evaluations of the mapping methods used revealed a variety of strengths and weaknesses

inherent in each method. The detailed analysis and results are in [5]. The Gantt and Ward/LEI methods proved the most useful for representing process characteristics. The process mapping, DSM, and Rother and Shook maps gave the user the most versatility in analyzing and changing the processes mapped.

The capabilities of the tools as used at the various sites were normalized to a rating of relative capability. The ratings went from 0 to 1; were 0 is useless and 1 as good as any tool considered.

The as-used tool capability was compared to the lean context rating and the self-assessed metric of success, with interesting results. Figures 2-4 show the correlations of tool capability and success, lean context and success, and tool capability and lean context. All factors are correlated. This confounds the effect of tool capability on process improvement success, but strongly suggests that good tools and lean context are both necessary (or at least correlate with) process improvement success.

No single best practice was identified, but the highest as-used capability ratings went to sites using process flow maps, DSM analysis, or combinations of the two. This observation is the basis of the suggested method in the section that follows.

5 Suggested Methods

No one "best practice" was identified from the cases studies. Instead, an integration of tools known to be effective from the case studies is presented here. In this section, a suggested method for VSA/M for PD will be outlined. It is described in greater detail in [5].

5.1 Context

First, the context in which the tools are used must be appropriate. The creation of a lean context in an enterprise is well beyond the scope of this work; interested readers are referred to LAI work in this area, e.g. [20]. Creating the right context in the process improvement effort is summarized in [5], which suggests the following steps to set up a value stream analysis-based improvement effort:

1. Assemble and train VSA/M team
2. Select Value Stream to improve
3. Define Value Stream elements
4. Analyze and map Current State
 - a) Analyze and map Future State
 - b) Analyze and map Ideal State
5. Implement new process
6. Continuous improvement

5.2 High-level representative mapping

No one value stream mapping method was found that did all jobs well. It was also noted in the case studies that high-level looks at PD processes were vital to provide context to lower level analyses. However, they tended not to provide much insight into process improvement, as at a high level most processes are value added. Therefore, a progression is suggested:

1. A high-level representative tool to aid in defining the Value Stream and its context,
2. A detail-level process flow map to aid in the determination of flow and value, and
3. A Design Structure Matrix (DSM) to aid in the determination of process structure, groupings, iterations, and concurrency.

Representation of the high-level process with a Gantt chart or Ward-type map can help to provide an initial “big picture” of the process. As the previous section noted, these maps are best for representing the actual nature of a process.

5.3 Detailed mapping for analysis

Previous VSA/M efforts have found it most helpful to “drill-down” from the high-level process to focus on more detailed analysis, where inefficiencies become more apparent. As determined in the research data reduction, a process flow map best allows for the analysis of flow and value, while a DSM will further aid analyzing the structure, concurrency, and iteration aspects of a process.

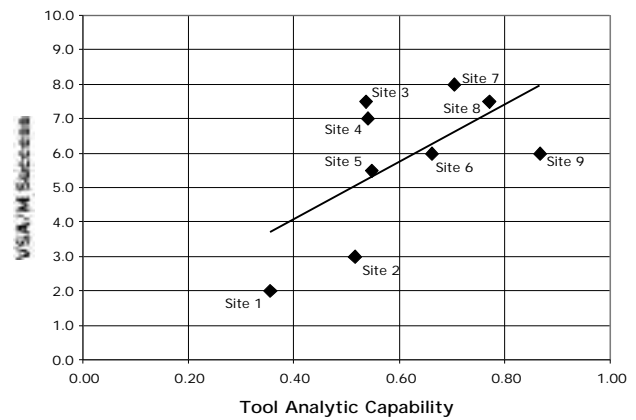


Figure 2. Tool analytical capability correlates with process improvement success

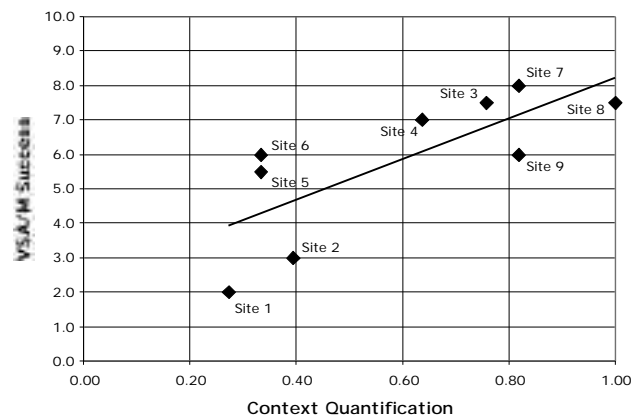


Figure 3. Lean context correlates with process improvement success

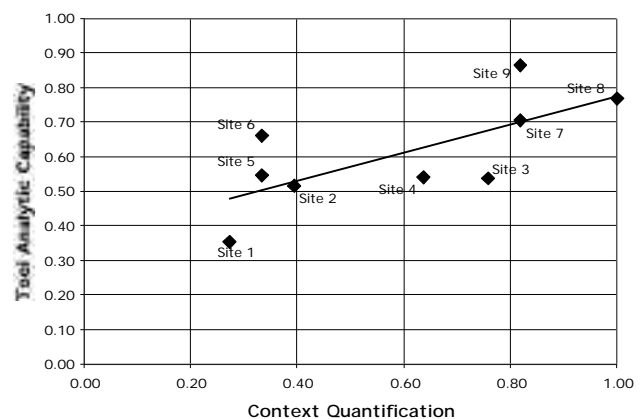


Figure 4. Tool Analytical capability correlates with lean context

In the example to follow, we introduce a customized process map format particularly suited to PD value stream mapping [5].

The most difficult step in the VSA/M process is not the mapping, however. It is the collection of the necessary data on the current state of the process. Three levels of depth of data collection and analysis were identified in the case studies:

1. Mapping activities and inputs/output
2. Capturing metrics and characteristics of each activity
3. Consideration of activity value

Data for each level is harder to collect, but allows more detailed analysis. We will pursue an example assuming that the levels of data are collected and analyzed in sequence; this has obvious inefficiencies in practice. For any given process improvement effort, the appropriate level and data collection strategy (e.g. sequential vs. simultaneous) should be decided.

Figure 5 is a notional data collection sheet. It is not intended as a template for any given effort, but gives a feel for the data to be collected. The method used for the data collection, whether it be interview, participation, or observation studies, may vary depending on the nature of the process to be improved. However, past VSA/M efforts have revealed the importance of taking the data from sources close to the process. This may include “walking” through the process with the team, or speaking to the actual personnel completing the process. It should most likely not rely solely on the given Work Breakdown Structure (WBS) or collective team knowledge. WBS’s, or similar process documentation, have been shown to conflict with what actually takes place in the process. Conventional tacit knowledge (e.g. what would be collect in a single brainstorming session) should also be challenged by direct observation.

5.3.1 Activities and inputs/outputs

The unshaded portions of Figure 5 represent basic information on the activities in the value stream and their inputs and outputs. Collecting this information should allow the construction of the first level of process and DSM maps.

Figures 6 and 7 show the results of a level one data collection and mapping for a preliminary design process.

The process map gives a good visual feel for the order of the tasks and the forward flow of information between them. Significant reviews and handoffs are noted on the map. The DSM mapping shows the information exchange between processes in more detail. A dot in column *a*, row *b* indicates flow of information from process *a* to process *b*. Additional details, such as the need for the report task to collect data from all other tasks, and the possibility of major rework if the manufacturing planners require a change in the drawings (the dot in the upper right hand corner) are captured in this format.

5.3.2 Task metrics and characterization

The portions of Figure 5 shaded light red represent additional useful detail about the tasks. Basic metrics of the tasks such as how long it takes (elapsed time), how much of that time is spent in active work (in-process time), and how much of that work is “core process” (as opposed to set-up and other necessary wastes), as well as costs and resources used, and estimates of the likelihood of rework, are collected. These metrics can be added to the process map as shown in Figure 8 (which shows only two tasks from Figure 6 for clarity). This presentation allows an at-a-glance understanding of the process in more detail. For example, the inclusion of the time metrics allows quick adding up of the current and best possible durations of strings of sequential tasks. Data (such as the rework probability in Figure 5) can also be collected for more sophisticated DSM analyses (e.g. [19]) at this stage.

5.3.3 Consideration of value

Lacking a robust method for quantification of the value of individual PD tasks, previous VSA/M efforts have used the subjective ratings of value-added, necessary non-value added (enabling) and non-value-added activities. The

| General | | | | | | Resources | | | | | | | | | |
|--|--|----------------------|-------------------------|----------|--|---|--|-------------------|-------------------------|--|--|----------|--|---------------|--|
| Activity Name | | | FEM Development | | | Elapsed Time | | | 4 (days) | | | | | | |
| Location | | | Design Station #4 | | | In-process Time | | | 21 (hrs) | | | | | | |
| Pers./Org. Performing | | | Fernandez/Chase | | | Core Task Work Time | | | 19 (hrs) | | | | | | |
| Completion Criteria | | | model finished | | | Activity Based Cost | | | \$1,350 | | | | | | |
| Success Criteria | | | analysis with no rework | | | Special Resources Req. | | | design station/software | | | | | | |
| Other: | | | | | | Chance of Rework/Time | | | 33 % 5 (hrs) | | | | | | |
| Input #1 | | | Input #2 | | | Input #3 | | | | | | | | | |
| Name | | Stability & Control | | | | Name | | Structural Rqmts. | | | | Name | | | |
| Sender | | Kirtley | | | | Sender | | Uzair/Chambers | | | | Sender | | | |
| Transfer | | Documentation Report | | | | Transfer | | electronic file | | | | Transfer | | | |
| Quality | | 1 2 3 4 5 N/A | | | | Quality | | 1 2 3 4 5 N/A | | | | Quality | | 1 2 3 4 5 N/A | |
| Utility | | 1 2 3 4 5 N/A | | | | Utility | | 1 2 3 4 5 N/A | | | | Utility | | 1 2 3 4 5 N/A | |
| Format | | 1 2 3 4 5 N/A | | | | Format | | 1 2 3 4 5 N/A | | | | Format | | 1 2 3 4 5 N/A | |
| Output #1 | | | Output #2 | | | Output #3 | | | | | | | | | |
| Name | | FEM model | | | | Name | | | | | | Name | | | |
| Receiver | | Walton | | | | Receiver | | | | | | Receiver | | | |
| Transfer | | electronic file | | | | Transfer | | | | | | Transfer | | | |
| Purpose | | Allow SS&L Analysis | | | | Purpose | | | | | | Purpose | | | |
| Critical Drivers | | | | | | sensitivity of FEM software: varies based on type of model, and often causes rework | | | | | | | | | |
| (metrics/attributes) | | | | | | | | | | | | | | | |
| Context (interaction with other VS) | | | | | | | | | | | | | | | |
| Value | | | | | | | | | | | | | | | |
| Non-Value-Added | | | | Enabling | | | | Value-Added | | | | | | | |
| 1-----2-----3-----4-----5 | | | | | | | | | | | | | | | |
| Functional Perform. | | 1 2 3 4 5 N/A | | | | Enabling Activities | | 1 2 3 4 5 N/A | | | | | | | |
| Defn. of Processes | | 1 2 3 4 5 N/A | | | | Cost/Schedule Savings | | 1 2 3 4 5 N/A | | | | | | | |
| Reduction of Risk | | 1 2 3 4 5 N/A | | | | Other: | | 1 2 3 4 5 N/A | | | | | | | |
| Form of Output | | 1 2 3 4 5 N/A | | | | Other: | | 1 2 3 4 5 N/A | | | | | | | |
| Waste Sources | | | | | | | | | | | | | | | |
| Waste of Resources | | | | | | | | | | | | | | | |
| Waste of Time | | | | | | | | | | | | | | | |
| Waste of Quality | | | | | | | | | | | | | | | |
| Waste of Opportunity | | | | | | | | | | | | | | | |
| Information Waste | | | | | | | | | | | | | | | |
| Other: | | | | | | | | | | | | | | | |
| Comments/Suggestions | | | | | | | | | | | | | | | |
| (improvement ideas, problems, stress points) | | | | | | | | | | | | | | | |

Figure 5. Sample data collection sheet

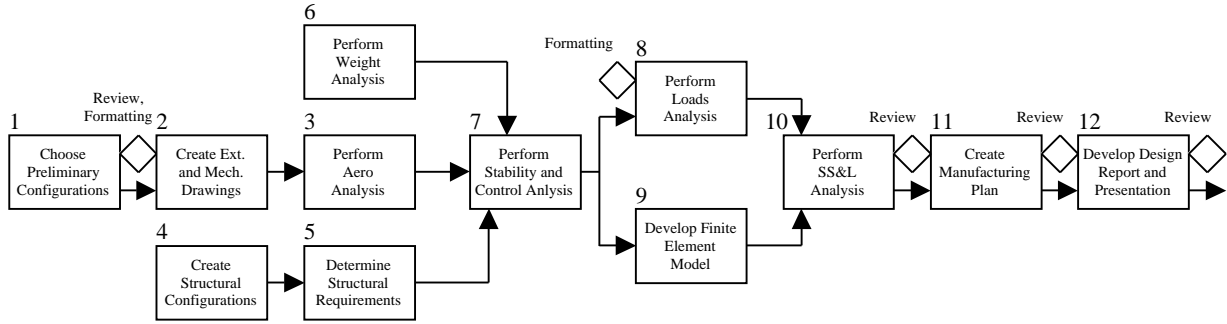


Figure 6. Process map

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|----|---|---|---|---|---|---|---|---|---|----|----|----|
| 1 | 1 | | | | | | | | | | | |
| 2 | • | 2 | • | | | | | | | | | • |
| 3 | • | • | 3 | | | | | | | | | |
| 4 | • | | | 4 | • | | | | | | • | |
| 5 | | | | • | 5 | | | | | | | |
| 6 | • | | | | | 6 | | | | | | |
| 7 | • | | • | | • | • | 7 | | | | | |
| 8 | | | | | | | • | 8 | | • | | |
| 9 | | | | | | | • | | 9 | | | |
| 10 | • | | | | | | | • | • | 10 | | |
| 11 | | | | | | | | | | | • | 11 |
| 12 | • | • | • | • | • | • | • | • | • | • | • | 12 |

Figure 7. Process DSM

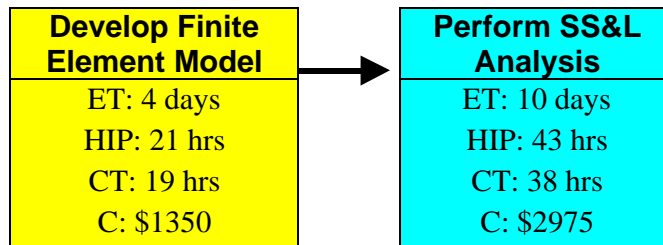


Figure 8. Metrics and value in process map

data collection sheet also provides additional tools for making a more sophisticated judgment of value. Different types of value, as explained in [5] and in more detail by Chase [14], may be assessed. Considering types of value rather than an absolute (yet very subjective) rating is also better for team morale – it is preferable to be provide risk reduction and task enabling value than to be judged “necessary non-value-added.” Similar judgments may be applied to the quality of information provided to activities. Value may be displayed on the process map in a

variety of ways. In Figure 8, the model development is shaded light yellow to indicate enabling; the analysis darker blue to show risk reduction.

Known sources of waste, as observed by those actually performing the process, should also be assessed at this time. The data collection sheet gives some examples of waste categories, but this is not meant to be an exhaustive list. Other sources of waste (e.g. Table 1) may well be considered. Finding waste

is the focus of much lean training, and will not be explained in detail here.

5.4 Finding a future state

A well-documented value stream allows understanding of the process and points the way towards improvement. Some improvements can be seen quickly and visually, others require some process. The literature has several examples of finding future states for manufacturing processes [7,10], and some for PD, e.g. [4]. Reference [5] suggests heuristics to apply to PD value stream maps to move them towards a lean state. They are product of both the case study results and LAI's Lean Enterprise Model.

1. Remove redundancy, simplify, and standardize
2. Create continuous flow of information
3. Minimize information handoffs
4. Balance reviews and responsibility
5. Improve communication systems
6. Implement integrated product and process development
7. Maximize concurrent processing

6 Concluding Remarks

Value stream mapping can be an important tool for product development process improvement. Aerospace industry experience indicates that both a good set of value stream mapping tools and a lean context correlate with process improvement success. No single best practice was found. However, lean terminology reassessed to apply to PD, combined with several complementary value stream mapping methods, provide an effective set of tools for PD value stream mapping.

References

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- [1] Murman E, et al. *Lean Enterprise Value*, p 72. Palgrave, 2002.
 - [2] Garvin D. The processes of organization and management. *Sloan Management Review*, Summer 1998.
 - [3] Murman E, et al. *Lean Enterprise Value*, p 209. Palgrave, 2002.

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- [4] Ibid, pp 125-127.
 - [5] Millard R. Value stream analysis and mapping for product development. Master's thesis, Massachusetts Institute of Technology, June 2001.
 - [6] Womack J, Jones E, and Roos D. *The Machine That Changed the World*. Harper Perennial, 1992.
 - [7] Womack J, and Jones E. *Lean Thinking*. Simon & Schuster, 1996.
 - [8] Clark K and Fujimoto T. *Product Development Performance: Strategy, Organization, and Management in the World Auto Industry*. Harvard Business School Press, 1991.
 - [9] Sobek D. Principles that shape product development systems: a Toyota-Chrysler comparison. Ph.D. thesis, University of Michigan, 1997.
 - [10] Rother M and Shook J. *Learning To See: Value Stream Mapping to Add Value and Eliminate Muda*. Lean Enterprise Institute, 1999.
 - [11] Schmidt M. Application of lean principles to an enterprise value stream: a lean analysis of an automotive fuel system development process. Master's thesis, Massachusetts Institute of Technology, January 2000.
 - [12] Workshop reports and proceedings at <http://web.mit.edu/lean>
 - [13] Ulrich K and Eppinger S. *Product Design and Development*. 1st edition, McGraw-Hill, 1995.
 - [14] Chase J. Value creation in the product development process, Master's thesis, Massachusetts Institute of Technology, 2001.
 - [15] Slack R. The lean value principle in military aerospace product development. Lean Aerospace Initiative Report RP99-01, Massachusetts Institute of Technology, 1999.
 - [16] Trischler W. *Understanding and Applying Value-Added Assessment: Eliminating Business Process Waste*. ASQC Quality Press, 1996.
 - [17] Sterman J. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Irwin/McGraw-Hill, 2000.
 - [18] The MIT Design Structure Matrix (DSM) home page, <http://web.mit.edu/dsm>
 - [19] Browning T. Modeling and analyzing cost, schedule, and performance in complex system product development. Ph.D. thesis, Massachusetts Institute of Technology, 1998.
 - [20] *Transitioning to a Lean Enterprise: a Guide for Leaders*. Lean Aerospace Initiative, Massachusetts Institute of Technology, 2000.