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Leanness Score of Value Stream Maps

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Abstract

A *Value Stream Map* (VSM) allows lean practitioners to visualize the performance and conditions of manufacturing systems. While creating visibility for improvement plans, a measure of overall leanness level is not inherent in the map. This research proposes a methodology to measure the overall leanness of a VSM considering *Cost*, *Time* and output *Value*. Value-added and non-value-added investments are identified to quantify the level of leanness. Using the Data Envelopment Analysis technique, the leanness measure delivers a self-contained, unit-invariant score of the mapped system to support decision making on continuous improvement.

Keywords
Data Envelopment Analysis (DEA), lean manufacturing, leanness measure, value stream mapping

1. Introduction

Streamlining the value stream of a manufacturing system or an extended enterprise is the key to becoming lean. The *Value Stream Mapping* technique developed by Rother and Shook [1] is one of the most powerful lean tools, yet easy to understand and implement. Through a value stream map (VSM), lean practitioners visualize the performance and conditions of the mapped systems. Current state and future state maps demonstrate the material and information flows and guide the improvement efforts. While gaining visibility, a VSM does not contain a measure of overall leanness level of the mapped system. Besides, with the emphasis on time-based performance in a VSM, decision makers may overlook the importance of other factors (e.g. cost, quality, customer satisfaction, etc.) and miss the opportunities for further improvement. Therefore, incorporating an integrated measure of leanness would enhance the decision-support information carried by a VSM. This paper proposes a methodology to measure the overall leanness of a VSM as complementary information for decision making.

In this research, the quantitative leanness measure developed by Wan and Chen [2] is adopted to evaluate the leanness level of manufacturing systems. Considering Cost and Time investments and output Value of a work piece, the leanness measure employs the Slacks-Based Measure (SBM), a mathematical model for Data Envelopment Analysis (DEA), to derive a self-contained, unit-invariant leanness score of a VSM. Value-added and non-value-added investments are identified as parameters of the model to quantify how lean the system is. By comparing future state maps resulting from different lean initiatives, the leanness scores evaluate the impacts of various lean tools and thus support the decision making for continuous improvement. Consequently, the leanness score of a VSM demonstrates the effectiveness of improvement efforts and displays opportunities of further improvement.

In Section 2, techniques developed for value stream mapping are reviewed. Section 3 introduces the mathematical model of the quantitative leanness measure for manufacturing systems. Section 4 presents the implementation of the leanness measure on a VSM, including the data requirements and a reduced form of the mathematical model. Finally, applications and potential extensions of the leanness measure of a VSM are discussed, followed by future research directions in the conclusion.

2. Value Stream Mapping

Ever since the term “lean manufacturing” was coined by a MIT research group studying Toyota-style systems in the late 1980’s [3], the waste-elimination concept is showing increasing impacts on various industries. In order to eliminate all the non-value-added activities and pursuit perfection, the customer-driven *Value* must be fully addressed. Consequently, the components of a value chain must be linked and streamlined to become a continuous *value stream* as a whole [4]. The significance of value and value stream is further clarified in the *Lean Thinking* [5], which becomes the foundation of the development of value stream mapping techniques.

A set of value stream mapping tools was initially developed by Hines and Rich in 1995 [6] [7]. In response to the widely recognized “seven types of waste” defined by Ohno [8], seven *value stream mapping tools* were created to help lean practitioners identify waste and the appropriate routes to improvement [6].

- Process activity mapping
- Supply chain response matrix
- Production variety funnel
- Quality filter mapping
- Demand amplification mapping
- Decision point analysis
- Physical structure mapping

A five-stage approach is suggested to systematically implement the tool set for the best result. This methodology was applied intensively in the late 1990’s within the Lean Processing Programme (LEAP) in U.K. [7]. However, results of the implementation reveal the weakness of the tool set, including limited coverage of wastes, missed improvement opportunities, and difficult to understand and implement. The research group later developed additional tools, such as the *Value Analysis Time Profile* [9], for value stream management; yet, very limited impact has been delivered.

On the other hand, Rother and Shook [1] developed another tool for value stream mapping, which becomes one of the most powerful tools for lean implementation. The mapping is a paper-and-pencil approach, which can be carried out easily and demonstrates the material and information flows effectively. This technique graphically maps out the processes of a manufacturing system, including value-added and non-value-added activities, and provides the information of time-based performance for further analysis. As illustrated in *Learning to See* [1], a current state map and a future state map are generated when an improvement project starts. The current state map shows the performance and conditions of the mapped system; while the future state map serves as the target of improvement actions. By comparing the maps of the two stages, the tool provides a hint to “how lean the system can be” and “how to achieve the leanness.” From there, improvement tactics can be determined to guide the actions of waste reduction and direct the system toward the proposed future state. The maps are reviewed periodically to track the progress of improvement and determine whether the two maps need to be redrawn.

Due to its simplicity, the tool is easy to use and understand and is very effective. It can be applied to various types of value streams, including non-manufacturing systems, as long as the customer-driven value and value stream can be defined clearly. Several extensive applications have been proposed based on this tool. Duggan [10] introduces detailed procedures to apply the VSM tool on the mixed model production. Tapping et al. [11] integrates the mapping tool with the overall lean implementation context into a systematic value stream management approach. For the non-manufacturing applications, Tapping and Shuker [12] developed a methodology to apply the VSM tool in administrative areas in order to achieve a lean office environment. After applying lean improvements on all the components of a supply chain, the individual sections of value stream must be connected and streamlined. Jones and Womack [13] broaden the scope of the conventional VSM tool to cover the *Extended Value Stream*, which aims for achieving the lean extended enterprise and lean supply chain.

Due to the “just-in-time” nature of lean manufacturing, the performance information associated with a VSM has an emphasis on time-based competitiveness. Efficiencies of manufacturing processes, material handling, and inventory management are typically displayed in time units. A VSM demonstrates overall performance of the system through a line of time with detailed time-based performance in separate data boxes [1]. Takt time, cycle time, changeover, uptime, and time in inventory are the most common metrics shown in a VSM [1] [10] [11]. Later versions of VSM include a wider range of performance information, such as the quality and delivery screen in the extended VSM [13]. Although more performance metrics have been included, the VSM tool itself does not provide a quantitative measure of the overall leanness. The lack of appropriate measure for overall leanness is the main reason. Allen et al. [14] introduce a *VSM Calibrate* that shows the results of leanness assessment on a radar chart. A current state calibrate and a future state calibrate are generated based on the two stages of VSM; thus, the current leanness level and potential improvement can be displayed. However, the leanness assessment based on predefined performance indicators is inevitably subjective. A quantitative leanness measure developed by Wan and Chen [2] provides a solution to measuring the overall leanness of a VSM. This leanness measure is introduced in the next section.

3. A Leanness Measure Based on Data Envelopment Analysis (DEA)

In order to quantify the leanness level of manufacturing systems, Wan and Chen [2] propose a leanness measure based on the *Data Envelopment Analysis* (DEA) techniques. DEA is a methodology developed for performance measurement [15]. A DEA model identifies the best practices of Decision Making Units (DMU) from a historical data set to determine the technical frontier, namely the benchmark of efficiency scores. DMUs are the observations of a transformation process to be evaluated. In the proposed DEA-Leanness measure, the production process of each work piece forms a DMU. The total *Time* and *Cost* investments on the production and the output *Value* of the product are the input and output variables of the DEA model. In order to identify the benchmark for measuring leanness of a VSM, the DEA-Leanness measure uses virtual DMUs to push the frontier toward ideal leanness and deliver more accurate leanness scores. *Ideal DMU*s (IDMU) are virtually created by removing the non-value-added (NVA) time and cost from the input variables of the *Actual DMU*s (DMU). Therefore, the IDMUs, with only the value-added (VA) time and cost, represent the ideal performance of the production processes.

The Charnes-Cooper-Rhodes (CCR) model, a fractional program developed in 1978, is the first mathematical model of the DEA technique to derive the efficiency score [16]. However, the scores derived from the CCR model do not include the inefficiency caused by slacks, which are the input excesses or output shortfalls of a benchmarking DMU [2]. As a result, scores of the CCR model overestimate the actual efficiency if slacks exist. To address this weakness of the original DEA model, Tone [17] proposes a *Slacks-Based Measure* (SBM) of efficiency that deals directly with the input excesses and output shortfalls of DMUs. The SBM score is also unit-invariant and monotone-decreasing with respect to slacks. Using the input/output variables of DMUs defined for DEA-Leanness measure, the fractional program is listed as follows. It can be further transformed into an equivalent linear program for solution [18].

$$\text{Min.} \quad \rho_{lean} = \frac{1-(\frac{1}{2})(\frac{s_T^-}{x_{T0}}+\frac{s_C^-}{x_{C0}})}{1+\frac{s_V^+}{y_{V0}}} \tag{1}$$

$$\text{Subject to} \quad x_{T0} = \sum_{i=1}^{n} x_{Ti}\lambda_i + s_C^- \tag{2}$$

$$x_{C0} = \sum_{i=1}^{n} x_{Ci}\lambda_i + s_C^- \tag{3}$$

$$y_{V0} = \sum_{i=1}^{n} y_{Vi}\lambda_i - s_V^+ \tag{4}$$

$$\text{Where } \lambda,\ s_T^-,\ s_C^-,\ s_V^+ \ge 0$$

<u>Notation:</u>

ρ_{lean}: Leanness Score
x_{T0}: Input Time of DMU_0
x_{C0}: Input Cost of DMU_0
y_{V0}: Output Value of DMU_0
n: Number of DMUs
λ: SBM Weights for DMUs
s_T^-, s_C^- and s_V^+: Slacks associated with Inputs/Output

With the DEA-Leanness measure, the leanness score of a VSM can be derived. However, a typical VSM does not include information of costs or product value in the map. These data needs to be collected in addition to the time-based performance data. Details of the scoring of a VSM are introduced in the following section.

4. Measuring Leanness of Value Stream Map

A typical VSM comes with time-based performance, such as time in process, waiting in buffer, time in inventory, etc. An example VSM of three production processes is shown in Figure 1. In the original DEA-Leanness measure [2], the data of input/output variables are obtained from detailed information of each work piece. Unlike the original measure, the measurements of performance metrics associated with a VSM are derived from aggregated data. For example, an average processing time is calculated as the total processing time of a machine divided by the number of pieces processed by the machine. Similarly, the amount of inventory divided by the daily demand gives the average time in inventory. Collecting the aggregated data is usually more convenient than timing every work piece going through the production line. Therefore, obtaining the time averages of a VSM requires less effort than collecting detailed data from the individual work piece. The averages are capable of representing the general conditions of the value stream. However, an average number cannot display the variability of the actual conditions. The lost information may contain clues of the actual leanness level and potential improvements.

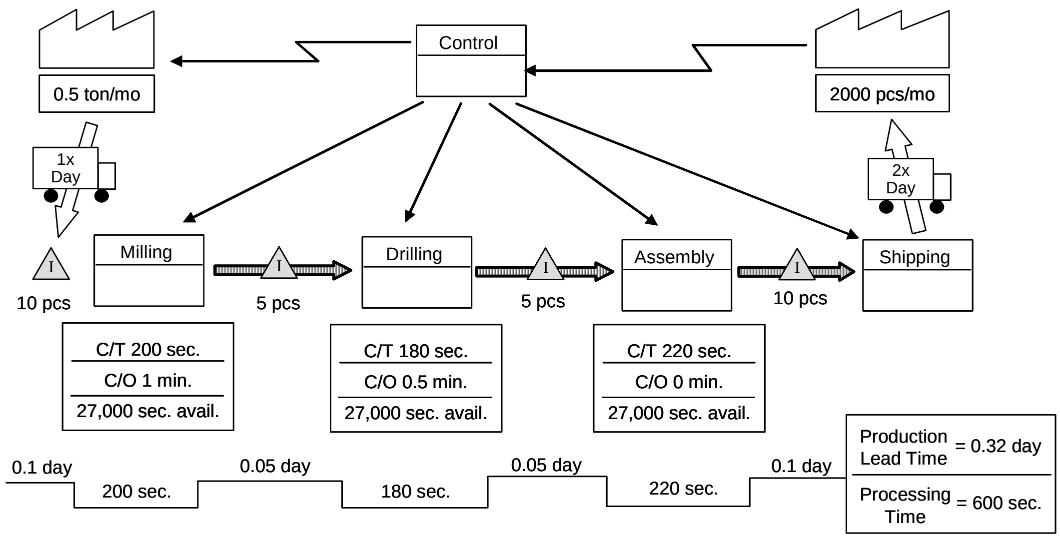

Figure 1: Example Value Stream Map with Three Production Processes [18]

For the DEA-Leanness measure of an existing VSM, the *Time* data can be collected directly from the map, but *Cost* and *Value* are not readily available. The missing data needs to be collected in order to create a corresponding IDMU. Following data entries are needed to construct the ADMU and IDMU for the exiting VSM [18].

- **Time:** The total time for a work piece to flow through the system is represented as "Production Lead Time" in the VSM. From Figure 1, this number (0.32 day) can be used directly as the time variable of a DMU. The unit of the time needs to be consistent with the VA Time of the IDMU. In this example, the available work time is 27,000 seconds (or 7.5 hours) per day. Therefore, the production lead time 0.32 day is equivalent to 8700 seconds.
- **Cost:** The average cost for a work piece to flow through the value stream can be calculated as the total cost of daily (or monthly) production divided by the quantity of product delivered per day (or per month). Here the total cost includes the material cost, direct processing cost, and indirect costs. Thus, all the VA and NVA costs should be included. The denominator uses the actual amount of finished products so that the costs of rework and scrap can also be included.
- **Value:** The output value can be calculated as the retail price multiplied by customer satisfaction rate, where the satisfaction rate should reflect quality and functionality of finished product, on-time delivery, and other factors that affect the customers' perception of the experience of purchasing this product. The IDMU uses the same value because the value of an IDMU cannot be assumed to be perfect when using the VA time and cost obtained from the ADMU.
- **Value-Added Time:** The "Processing Time" in the VSM is the VA Time of an IDMU. Therefore, the number can be used directly. In the example VSM, the VA time is 600 seconds.
- **Value-Added Cost:** The VA Cost of an IDMU cannot be obtained directly from the VSM, and it should be analyzed for each VA process. For a VA process, the VA cost of daily (or monthly) production should

include material cost and direct processing costs. To obtain the VA cost of one work piece, divide the daily (or monthly) VA cost by the total amount of work piece in that period excluding scrapped pieces because the costs allocated to scrapped pieces are not value-adding.

The procedure of acquiring the *Cost*, *Time*, and *Value* data for the DEA-Leanness Measure is summarized in Table 1 along with a numerical example given in the last column of the table.

Table 1: Preparing Data for DEA-Leanness Measure based on Existing VSM [18]

	Variable	Procedure	Example
ADMU	**Time**	"Production Lead Time" from VSM	0.32 days = **145** minutes
	Cost	$\frac{\text{Daily Cost of Production}}{\text{Daily Amount of Delivered Products}}$	\$1000.00 / 10 units per day = \$**100.00** per unit
	Value	(Retail Price) x (Customer Satisfaction)	\$120 x 95% = **114**
IDMU	**VA Time**	"Processing Time" from VSM	600 seconds = **10** minutes
	VA Cost	Sum ($\frac{\text{Daily VA Cost of a VA Process}}{\text{Delivered Amount x (1+Scrap Rate)}}$)	\$500/(10x1.05) +\$200/(10x1.02) +\$100/(10x1.01) =\$**77.13** per unit
	Value	(Retail Price) x (Customer Satisfaction)	\$120 x 95% = **114**

Based on the data collection, a pair of ADMU and IDMU can be created for leanness evaluation. From Equation (1) to (4), a reduced form of DEA-Leanness measure can be derived as in Figure (5), which delivers the same leanness score when an ADMU/IDMU pair is the only data points. Consequently, the leanness score of the example VSM is calculated as follows and summarized in Table 2.

ADMU (x_{TA}, x_{CA}, y_{VA}) = (145, 100, 114)
IDMU (x_{TI}, x_{CI}, y_{VI}) = (10, 77.13, 114)

$$\text{Leanness Score} = \frac{1-(\frac{1}{2})(\frac{x_{TA}-x_{TI}}{x_{TA}}+\frac{x_{CA}-x_{CI}}{x_{CA}})}{1+(\frac{1}{1})(\frac{x_{VI}-x_{VA}}{x_{VA}})} = 0.42 \quad (5)$$

Table 2: Leanness Score Derived from the VSM Example

DMUs	Leanness Score	*Slack*		
		Time	**Cost**	**Value**
ADMU	**0.420**	135.000	22.870	0.000
IDMU	**1.000**	0.000	0.000	0.000

As a result, the leanness score of the mapped system is 0.42. The pair of ADMU and IDMU is created based on the average time, cost, and value of a selected time period. Using the same procedure, different pairs of ADMU and IDMU can be created for different periods of time. Therefore, more than one pair of DMUs can be created, and the leanness level of different time windows can be compared.

The resulting leanness score indicates "how lean the system is" or "how much leaner it can become." It is a synthesized metric with multiple dimensions, and the space for improvement in the individual dimension is shown as slack in Table 2. Since the DEA-Leanness measure is monotone increasing to the slacks, any increment in the NVA cost or time will lower the score and vice versa. Therefore, the score of different timeframes of a VSM can be compared. As for the accuracy of the benchmark, it has been concluded that the changes in VA cost and time are usually limited, unless dramatic advancements in production technology or management technique are introduced [18]. Therefore, the IDMU with VA cost and time represents a reasonable benchmark. However, creating IDMUs from average numbers may average out the best configuration of DMUs. Hence, the resulting leanness score may slightly overestimate the actual leanness level of the mapped system.

5. Conclusions

Value stream mapping has become one of the most popular tools for lean implementation. While simple and effective, the VSM tool does not offer an overall evaluation of the leanness level. This paper proposes a methodology to quantify the leanness level of manufacturing systems based on an existing VSM. The measure employs DEA techniques to identify the leanness frontier as a benchmark for the leanness score. A reduced form of the mathematical model of DEA-Leanness measure can be used when only one pair of DMUs is compared. The resulting leanness score indicates "how lean the system is" or "how much leaner it can become."

Since the application of VSM has been extended to various systems, the proposed leanness score of VSM can also be applied to different types of value stream, including manufacturing and non-manufacturing sectors. The leanness level of a supply chain can be evaluated by using the extended value stream maps. However, collecting additional data from systems as complex as a supply chain may require much more effort than collecting from a production line. A systematic approach should be developed to carry out the data collection in the future. Finally, the leanness score implies how much waste currently exists in the system. How to use this information to further identify improvement opportunities is another direction of continuing research.

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Biographical Sketch

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