An Integrated Metric to Assess Leanness Level Based on Efficiency, Flow and Variation

Ahmed Deif *
California Polytechnic State University, CA, USA

Abdul-Wahab Janfawi
University of Regina, SK, Canada

Rehab Ali
Nile University, Cairo, Egypt

This paper presents a new integrated metric to assess the leanness level of a manufacturing system. The new metric (EFV) is based on measuring the efficiency (E), the flow type (F) and the variability level (V) within the system. The quantitative approach of the metric is augmented with an expected range for the metric values to be able to visualize and position the relative performance of the system and track its improvements. A case study illustrated the practical impact of the developed metric and assessment approach. The results of leanness assessment in the case study pointed to various areas of improvements in the facility leading to different focused lean initiatives and plans. The developed EFV metric will enhance the existing leanness measurement literature, help manufacturing managers and practitioners to measure the lean level of their organization, and finally assist in tracking lean initiatives impact during their lean transformation journey.
Keywords: Lean assessment, Efficiency, Flow and Variation.

* Corresponding Author. Email address: adeif@calpoly.edu

I. INTRODUCTION

In the last few decades, many organizations around the world use lean philosophy, principles and tools in order to enhance their competitiveness and reduce their wastes. The implementation of lean management in a system proved to support practitioners in enhancing the processes, workers and the overall system efficiency. However, after applying lean tools and techniques to a system, decision makers face significant questions as to how lean their system is, what is the lean level of their system, and are there further opportunities to become leaner? Practitioners may know their system is leaner than before but they do not know how much leaner they must become. In the practice of lean management, the question is not only how to transform into a lean manufacturing system, but also how to measure the leanness level of a company. Thus, decision makers need a measurement tool or metric to assist them in understanding the leanness of the system and how much the system requires transferring to a leaner target.

This paper proposes an integrated metric to measure the leanness level of a manufacturing system from an efficiency, flow type and variability (EFV) stand point. This metric also highlights the weakness points from a lean perspective in the system to allow for further improvements. Additionally, it helps the practitioners in tracking the system improvement initiatives and feedback the leanness level. The importance of the developed metric lies in the opportunity to assess concurrently efficiency, variability and flow type of goods in one integrated measure. Having the ability to measure the lean level can assist an organization to be more comprehensive in improving productivity and facilitates the incorporation of the right tools that develop the system. The reason for choosing those three parameters in the developed metric is the fact that they capture three main characteristics in any of lean systems which are waste reduction, continuous flow and quality. Furthermore, the three parameters are related to each other and affect one another. This integrated metric will enhance the implementation and assessment of lean initiatives of a system in order to face the global market competition.

II. LITERATURE REVIEW

With the existence of various lean tools, few metrics exist to assess the leanness of manufacturing systems. The metrics are either used to evaluate the entire system or are dedicated to a specific operation or unit within the company. An early attempt towards a lean manufacturing system assessment was through the framework offered by MIT researchers called the "Lean Enterprise Self-Assessment Tool" (LESAT). It was used to evaluate the current situation of leanness in an organization (Hallam, 2003).

The manufacturing leanness was defined as a unifying concept by (Bayou & Korvin, 2008). They utilized a fuzzy-logic approach to measure the leanness degree of a manufacturing facility and compare the measured leanness level to a benchmark industry. Using another fuzzy approach, a multi-grade fuzzy was used as a tool to assess the leanness of an organization (Vinodh & Kumar, 2010-a). They further combined the fuzzy approach with the Quality Function Deployment (QFD) technique in (2010-b) to evaluate the degree of leanness in an organization. An efficient method was found to assess the lean of an organization using a Leanness Measurement Team (LMT) by (Singh & et al, 2010). Subsequently they tried to enhance the system's performance by figuring out the leanness level of the system and the requirements to increase the level of leanness. Also, a fuzzy approach was proposed by (Behrouzi & Wong, 2011) to evaluate lean systems based on questionnaire capturing main lean parameters. Furthermore, leanness assessment tool (LAT) was proposed by (Pakdil & Leonard, 2014) using both fuzzy based quantitative (directly measurable and objective) and qualitative (perceptions of individuals) approaches to assess lean implementation. The LAT measures leanness using eight quantitative performance dimensions: time effectiveness, quality, process, cost, human resources, delivery, customer and inventory. The LAT also uses five qualitative performance dimensions: quality, process, customer, human resources and delivery.

A unit-invariant leanness measure with a self-contained benchmark was proposed by (Wan & Chen, 2008) to quantify the leanness level of manufacturing systems. They used Data Envelopment Analysis (DEA) to determine the leanness frontier as a benchmark with which to make lean decisions and then measure the cost, time and value-adding investments of the decisions based on improvement outputs. In the same direction and unlike traditional systems which consider the accumulation of costs or timing and not both, Cost Time Profile (CTP) was used by (Rivera & Chen, 2007) as a tool to indicate Cost-Time Investments (CTI) in an organization and then measure the lean level of an organization. By focusing on cost and time, the proposed tool evaluated the impact of implementing lean tools and techniques on the system's performance. A typical performance measures such as work-in-process (WIP) level and lead time was used by (Abdulmalek & Rajgopal, 2007) in their attempt to prove the applicability of lean tools in continuous manufacturing industries. They used a current state of value stream map and a future state of value stream map to distinguish the differences between the two states. Multiple industrial studies were conducted by (Serrano et al., 2010) to investigate the use of the value stream map, not only as a tool in regard to processing improvement, but also as a system assessment tool.

A qualitative approach was used by (Soriano-Meier & Forrester, 2001) based on a questionnaire and interviews in order to assess the potential of applying lean tools to enhance a short-term competitive strategy. In addition, they used the Degree of Adoption (DOA) technique to illustrate the degree of lean production practices with work organization in the production and operation function. The same qualitative approach was employed by (Shetty et al., 2010) of a structured questionnaire to develop a score based lean metric. They designed an inclusive numerical lean evaluation for manufacturing organizations. Another survey approach was used by (Shetty et al., 2010) to assess the implementation of lean Six Sigma in an organization. They used software as an analyzer and then used Cornball's alpha to show the experimental results. The level of implementation of lean practices was illustrated by (Doolen & Hacker, 2005) using a structured survey in several small and large organizations. They reviewed five surveys focusing on evaluating a set of lean practices such as Just-in-time (JIT) and Total Quality Management (TQM).

A web-based Decision Support (DS) tool was used by (Wan & Chen, 2009) as an adaptive lean assessment. The purpose of the (DS) tool is to fulfill lean practitioners' needs by evaluating system performance and identifying the weaknesses within a system. A set of integrated metrics was proposed by (Duque & Rivera, 2007) such as monitoring the progress of a lean implementation, continuous monitoring, and benchmarking which were proposed individually by different authors. However, the proposed metric has limitations due to the requirement of conducting a technical investigation to confirm the results. The Mahalanobis Distance (MD) was used by (Srinivasaraghavan & Allada, 2005) as an evaluation tool with which to provide a quantitative measure of leanness. The mahalanobis distance method is a technique that distinguishes the pattern between two groups. A lean assessment tool was proposed by (Deif, 2012) focusing only on variability mapping as an extension for the known value stream mapping introducing variability index (VI) as a quantitative metric.

From the analysis of the previous work, it was shown that some work employed qualitative approaches that failed to quantify and track the real leanness of the system. In addition, some of the quantitative approaches (based mainly on fuzzy tools and surveyed data) suffered from various degrees of subjectivity that question the generality of the assessment tools in terms of relevance and applicability. A few other assessment approaches were computationally exhaustive making them difficult to fit within the lean paradigm that requires effectiveness and ease of application. A need to quantitatively capture the main aspects of a leanness level is required. Metrics developed for this task must be effective and able to measure and track the overall leanness of the system during and after lean implementation. The developed EFV metric is proposed to fulfill this need.

III. EFV LEAN ASSESSMENT METRIC

An integrated metric is introduced to measure the leanness level of a manufacturing system. The proposed metric is composed of three parameters namely; flow type of goods (F), efficiency (E), and variability (CV) (Equation 1). The reason for choosing those three factors is that they affect the whole manufacturing performance and impact the stability of the system. While variability acts against the good performance of a system, high efficiency and smooth flow are an essential step in the manufacturing excellence of factories. The improved efficiency and flow types of goods are two factors that push products smoothly within the systems towards more leanness. In contrast, variability hinders product flow and act against leanness of the system as depicted in Fig.1.

$$EFV = \sum_{i=1}^{m}\sum_{j=1}^{n} E_{ij} + \sum_{i=1}^{m-1} F_i - \sum_{i=1}^{m} CV_i \quad (1)$$

3.1. Metric Notations

CV_i : Coefficient of Variation.
D : Customers Demand.
EFV : Efficiency − Flow − Variability metric.
EFV°: Ideal Efficiency − Flow − Varability metric.
E_{ij} : Total system efficiency.
E_q : Quality efficiency.
E_t : Efficiency of time.
E_{th} : Throughput efficiency.
E_{wip} : Work-in-process efficiency.
F_i : Flow type of goods.
I_m : Ideal waiting time of machines.
I_w : Ideal waiting time of workers.
m : Number of stages.
M_p : Transportation waste time of product.
M_w : Waste motion time of workers.
n : Number of machines.
Th : Actual Throughput.
Th° : Ideal throughput rate.
T_i : Idle waiting time for both the machine and worker.
T_m : Motion time for both the time of transportation and the time of motion.
v_t : Value added time.
w : Efficiency weight.
WIP : Actual work − in − process.
w_t : Waste process time.

3.2. Metric Development

3.2.1. System's Efficiency

The proposed efficiency (E) parameter integrates several system parameters' efficiencies. It is the overall sum of time efficiency E_t, work in process efficiency E_{wip}, throughput efficiency E_{th} , and quality efficiency E_q. The reason for choosing the aforementioned efficiencies is that they interact to eliminate main waste forms and lean is all about waste reduction.

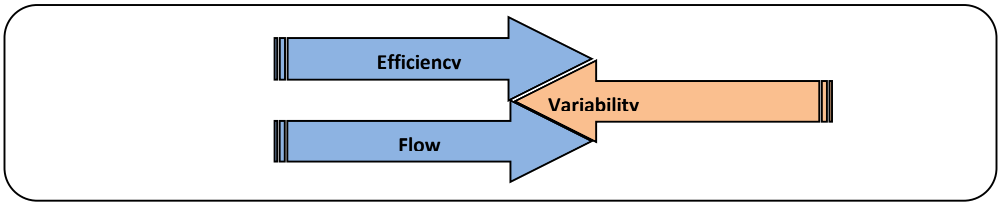

FIGURE 1. VARIABILITY ACTS AGAINST EFFICIENCY AND CONTINUOUS FLOW TYPE IN SYSTEM LEANNESS

3.2.1.1. Time Efficiency E_t

To determine the system's time efficiency, it is necessary to calculate the efficiency of the process by giving the relative measure of the sum of value added time (V_t), over the sum of the overall process time, which is the summation of both waste process times (W_t) and value added process time (V_t) (Equation 2).

$$E_t = \frac{\sum V_t}{\sum W_t + \sum V_t} \quad (2)$$

Waste time is composed of idle waiting time (T_i) and motion time (T_m) (Equation 3). Combining worker waiting time and machine waiting time into one parameter will give the overall idle wasted time (first parameter in equation 3). Additionally, the motion wasted times; the moving time for workers and lastly the transportation time of products are combined into one parameter that reflects overall motion waste time (second parameter in equation 3)

$$\sum w_t = \sum [T_i + T_m] \quad (3)$$

a) Idle Waiting Time (T_i)

$$T_i = \sum_{i=1}^{m} I_m + \sum_{j=1}^{n} \sum_{i=1}^{m} I_w \quad (4)$$

Equation 4 represents idle waiting time, which consists of both machine (I_m) and workers (I_w) idle waiting times.

b) Motion Waste Time (T_m)

$$T_m = \sum_{i=1}^{m} M_w + \sum_{i=1}^{m} M_p \quad (5)$$

The waste of moving time is the wasted time due to worker movement (M_w) (Equation 5). In addition, the transportation waste time is the wasted time of any form of product transportation (M_p) such as being transported by forklift. Summing workers moving waste time and product transportation waste time results in the total motion waste time.

3.2.1.2. Work in Process Efficiency (E_{wip})

$$E_{wip} = \frac{\sum_{j=1}^{n} \sum_{i=1}^{m} TH^{\circ} \times \sum_{j=1}^{n} \sum_{i=1}^{m} v_t}{\sum_{j=1}^{n} \sum_{i=1}^{m} WIP}$$

Where is $E_{wip} \leq 1$

(6)

The work in process efficiency (E_{wip}) is a relative measure of the ideal WIP which is calculated based on little's law (Hopp & Spearman, 2007) as the sum throughput of all machines at all stages multiplied by the sum value of time of all machines at all stages, over current WIP level of all machines at all stages (Equation 6).

3.2.1.3. Throughput Efficiency (E_{th})

$$E_{th} = \frac{\min\{Th, D\}}{\max\{Th, D\}} \quad (7)$$

Throughput efficiency is a relative measure of the minimum of either the overall process throughput or customer's demand (whichever is less), over the maximum of the overall process throughput or customer's demand (Equation 7). The difference between throughput and demand creates fluctuation in the throughput efficiency and it is a measure of the gap between the customer's demand and the throughput (production rate). This measure will capture any form of overproduction as a typical lean waste.

3.2.1.4. Quality Efficiency (E_q)

$$E_q = \frac{\sum_{i=1}^{m} \text{parts with no defects}}{\sum_{i=1}^{m} \text{parts with no defects} + \sum_{i=1}^{m} \text{parts with defects}} \quad (8)$$

The quality efficiency is the relative measure of the parts without defects over all produced parts (parts with no defects plus parts with defects as shown in Equation 8).

3.2.1.5. The Efficiencies Weights

$$E = w_1 E_t + w_2 E_{wip} + w_3 E_{th} + (1 - w_1 - w_2 - w_3)\, E_q$$
$$\text{where} \quad 0 \le E \le 1 \text{ , } w_1 = w_2 = w_3 = 0.25 \quad (9)$$

The calculation of the overall efficiency is simplified by multiplying the selected efficiencies by equal weights (Equation 9). Different values of the weights can be assigned based on the adapted marketing and production policies.

3.2.2. System's Variability

The process variability level is captured by sum of the coefficients of variations for every stage/process in the system (Equation 10). The CV is calculated by dividing the standard deviation over the mean of the cycle time for each stage (Equation 11). The coefficient of variation is considered the second moment of variation and is better in capture variability within the system (Hopp & Spearman, 2007) and (Deif, 2012). In this developed metric, the CV will range from 0 to 1. The reason for establishing a cap of 1 is based upon the authors actual industrial experience that indicates that the majority of industrial cases will fall within this range before going to a sever instability for values beyond one.

$$\text{Overall system variability} = \sum_{i=1}^{m} CV_i \quad (10)$$

$$CV = \frac{\sigma}{\mu} = \frac{\text{standard deviation}}{\text{mean}} \quad (11)$$

3.2.3 System's Flow Types

The assigned values for the flow type parameter in the developed metric is based on viewing the push flow type of goods as worst scenario from a lean perspective, while continuous flow types of goods are viewed as the best scenario from a lean perspective and finally the pull flow types of goods as an intermediate between the two policies (famous lean principle: if you cannot flow then pull). Therefore, flow type at each stage/process of the assessed system will be analyzed and then assigned a value of one if the flow was continuous, pull flow type will be assigned 0.5, and push flow type will be assigned zero. The sum of flow types at all stages is calculated as shown in Equation 12.

$$\frac{\sum_{i=1}^{m-1} F_i}{m-1}$$
$$\text{Where} \quad 0 \le F_i \le 1 \quad (12)$$

3.3 Metric Target

Effective metrics and assessment tools are preferred to have targets that reflect the ideal state of the measured system. If there is a clear and visible target, the employees in a company will strive and work hard to accomplish their target (Liker & Franz, 2011). The target in the developed integrated EFV metric is to reach the highest level of efficiency with minimal variation while having a continuous flow. The EFV target will help quantify how far the system's lean level is from the expected best leanness level defined by the developed approach. Based on the previous metric development, the target should be equal to two resulting from an ideal efficiency of

100% when is E = 1 and a continuous flow scoring also F = 1 on the metric range and with no variation where CV = 0. Using equation 1 the ideal EFV should be 1 + 1 – 0 = 2. In order to assess the relative performance of the overall leanness level of the system, the calculated overall EFV of the system will be divided by the ideal EFV target and then multiplied by 100 to illustrate the percentage of lean level and how lean the system is (Equation 13).

$$\text{EFV}=\frac{(\text{EFV})}{(2)}\times 100 = \text{Leanness level } \% \tag{13}$$

3.4. EFV Metric Application Methodology

Step one:
Measuring current leanness level.

This is achieved by collecting the system's data and using it in the developed the EFV metric, The manufacturers will thus determine the level of leanness in their organizations and will able to figure out how far they are from the target of leanness level defined by the developed metric.

As mentioned earlier, the theoretical best value of the EFV metric is two. In contrast, the theoretical worst value of the overall efficiency is zero, the flow type of goods is zero in the case of full push system, and for the variability in the whole system is one (where system is in real chaos). Thus the nominal lowest value of the EFV metric is minus one. Therefore, the expected range of the EFV metric is between minus one and two. In this paper, the range between the two limits will be divided into three zones to help the lean practitioners to assess their leanness level. The three zones are; Inefficient Performance (zone 1), Potential Improvement (zone 2), and Good Performance (zone 3). Further division of the range is also acceptable, however for simplicity and illustration the EFV range is divided into these three zones. Fig. 2 illustrates the three zones within the EFV range.

Step two:
Identifying improvement opportunities.

In step two, the manufacturer will study which zone their system fell into and in light of the values offered by EFV metric they will identify various weakness points within the system. This will open the door to improvement opportunities where manufacturers must focus on eliminating waste, converting process from push to pull, increasing the process efficiency, and reducing the process variability.

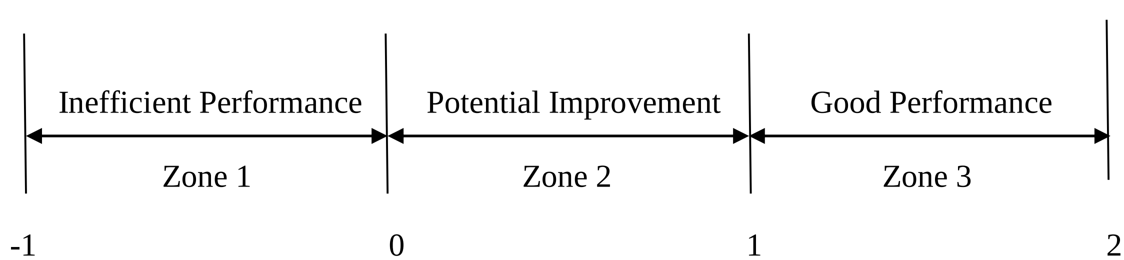

FIGURE 2. EFV METRIC RANGE

Step three:
Tracking leanness level improvement.

In step three, lean practitioners measure the system again after improvements to track the impact of these improvements on the leanness level with respect to the initial level of the system. They will also mark their new position on the EFV metric's range. The visual illustration given by the EFV metric range aligns with the visual control principle dictated by lean philosophy and thus helps mangers to easily spot their leanness level improvement. Furthermore, if there is any limitation in the system, it will be clear where the limitation is and where the areas requiring improvement are located.

IV. CASE STUDY

To demonstrate the application of the developed integrated lean assessment metric, a practical industrial case study is presented.

4.1. Factory's Background

The selected company is one of the largest steel pipe making companies in North America. A subsidiary of the manufacturing company, Tubular factory, was chosen for the leanness assessment and further improvement. Size of workforce in the factory is 55 with moderate level of automation. The factory produces a range of pipes - 30 inches in diameter to 60 inches in diameter and the rate of production is 150-200 pipes per day. The plant operates twenty-four hours a day, seven days a week, and 365 days a year. During each shift there is a 30 minutes break. Additionally, there is a coffee break which a worker can take at any time if the worker is not busy (free break).

Every pipe from the production line, if not defective, goes through eleven stages of process as shown in Fig. 3. The eleven stages are pipe making (using the technology of hot rolling), pipe cleaning, preliminary sonic inspection (PSI), internal inspection (ID), outside inspection (OD), X-ray inspection, final finishing, final visual inspection (FVI), final sonic inspection (FSI), scale, and the customer inspection stage. The pipes move from stage to stage via conveyors.

The process data was collected through multiple field visits over more than a year. Several random pipes were chosen to be analyzed. It is also important to note that all measurements were for a twelve hour shift. (See Appendix A, Table A1 for all measurements)

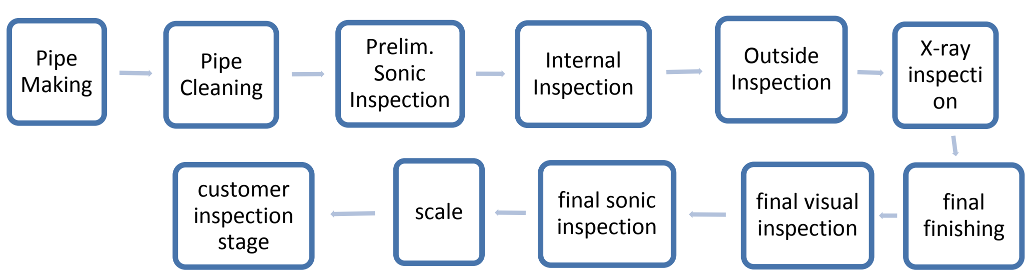

FIGURE 3. CONSIDERED STEEL PIPE FACTORY PROCESSES

4.2. Lean Assessment using EFV Metric

Process efficiency Calculations

a) Time Efficiency E_t

$$E_t = \frac{\sum_{i=1}^{11}\sum_{j=1}^{4} v_t}{\sum_{i=1}^{11}\sum_{j=1}^{4} w_t + \sum_{i=1}^{11}\sum_{j=1}^{4} v_t}$$

➢ Idle waiting time

$$T_i = \sum_{i=1}^{m} I_m + \sum_{j=1}^{n}\sum_{i=1}^{m} I_w$$

$$T_i = 72 + 60 = 132 \text{ min}$$

➢ Motion time

$$T_p = \sum_{i=1}^{m} T_m + \sum_{i=1}^{m} T_r$$

$$T_i = 263.5 + 245 = 508.5 \text{ min}$$

➢ The total waste time

$$\sum_{m=1}^{1}\sum_{n=1}^{4} w_t = (T_i + T_p)$$

= 132+508.5=640.5 min

➢ The total time efficiency

$$E_t = \frac{\sum_{i=1}^{11}\sum_{j=1}^{4} v_t}{\sum_{i=1}^{11}\sum_{j=1}^{4} w_t + \sum_{i=1}^{11}\sum_{j=1}^{4} v_t}$$

$$= \frac{79.5 \text{ min}}{640.5 \text{ min} + 79.5 \text{ min}} = 0.11$$

b) Work in Process Efficiency (E_{wip})

$$E_{wip} = \frac{\sum_{j=1}^{4}\sum_{i=1}^{11} TH^{\circ} \times \sum_{j=1}^{4}\sum_{i=1}^{11} v_t}{\sum_{j=1}^{4}\sum_{i=1}^{11} WIP}$$

$$E_{wip} = \frac{0.8 \frac{p}{min} \times 79.5 \text{ min}}{200 \text{ p}} = 0.32$$

c) Throughput Efficiency (E_{th})

$$E_{th} = \frac{\min\left\{\sum_{i=1}^{11}\sum_{j=1}^{4} Th,D\right\}}{\max\left\{\sum_{i=1}^{11}\sum_{j=1}^{4} Th,D\right\}} = \frac{100}{106} = 0.94$$

d) Quality Efficiency (E_q)

$$E_q = \frac{\sum_{i=1}^{11}\sum_{j=1}^{4} \text{parts with no defects}}{\sum_{i=1}^{11}\sum_{j=1}^{4} \text{parts with no defects} + \sum_{i=1}^{11}\sum_{j=1}^{4} \text{parts with defect}} = \frac{35}{175} = 0.2$$

e) Total Efficiency of the process

$$E = w_1 E_t + w_2 E_w + w_3 E_{th} + (1 w_1 + w_2 + w_3) E_q$$

$$E = (0.25 * 0.11) + (0.25 * 0.32) + (0.25 * 0.94) + (0.25 * 0.2) = 0.4$$

The result of the process efficiencies conducted is low efficiency in the process.

Process Variability Calculation

Cycle time variability for all processes is computed. The variability in each stage differs due to worker capability and the quality of machines. The values of standard deviation and mean of stages are shown in Appendix A, Table A2.

$$\text{Variability of stages} = \frac{0.2}{5} + \frac{0.3}{6.5} + \frac{0.7}{7.5} + \frac{0.2}{4} + \frac{0.6}{4} + \frac{0.5}{5} + \frac{0.4}{4} + \frac{0.7}{8.5} + \frac{0.6}{7} + \frac{0.8}{15} + \frac{0.3}{5} + \frac{0.9}{40} = 0.88$$

From the above calculations, the variability of the process is high.

Type of flow of Calculation

The flow type between stages is shown in Fig. 4. Continuous flow is witnessed between stage 1 and 2, stage 5 and 6, stage 6 and 7, stage 9 and 10 and stage 10 and 11. Push flow is between stage 2 and 3, stage 4 and 5, stage 7 and 8, stage 8 and 9. Finally, Pull flow is applied between stage 3 and 4 only.

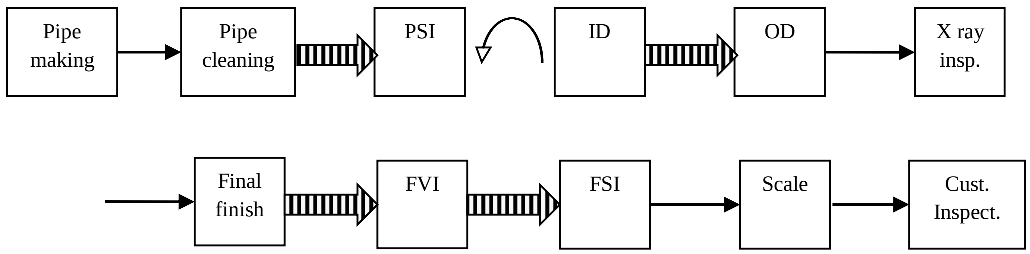

FIGURE 4. TYPE OF FLOW BETWEEN STAGES IN STEEL PIPE FACTORY
Where ⟶ denote continuous flow, ⇛ denote push flow, and ↶ denote pull flow.

The flow efficiency is calculated as the sum of flow values (as shown in section 3.2.3) and then divided by the number of stages.

$$F = \frac{\sum_{1}^{11-1} F_i}{10}$$

$$F = \frac{1+0+0.5+0+1+1+0+0+1+1}{10} = \frac{5.5}{10} = 0.55$$

EFV Calculation

After calculating the efficiency, variability, and flow type values for each stage in the process, EFV leanness metric is computed:

$$EFV = \sum_{i=1}^{m}\sum_{j=1}^{n} E_{ij} + \sum_{i=1}^{m-1} F_i - \sum_{i=1}^{m} CV_i$$

EFV= 0.4+0.55 - 0.88= 0.07

$$EFV_{lean} = \frac{(EFV)}{(2)} \times 100 = \text{Lean }\%$$

$$EFV_{lean} = \frac{0.07}{2} = 0.035 \times 100 = 3.5\ \%$$

The measured leanness level of the factory (within the scope of the selected parameters) lies in the second zone or the Potential Improvement zone where the EFV range begins at zero and ends at one. The measured system leanness level shows low efficiency, medium flow smoothness and high variability. The low leanness level captured indicates a wide opportunity for improvement and enhancement of the process.

4.3. Lean Assessment based on EFV Metric Results

The results of the proposed integrated metric assessment highlight three approaches to enhance the process by improving efficiency, flow type, and variability of the process. Results for each component are analyzed and then improvement approaches are suggested.

Process Efficiency

The metric shows that the system efficiency is low with value near medium (40 %). Time efficiency is 11 % which means that there are many non-value added activities that should be eliminated or reduced. The Idle waiting time is about 18 % of the total time. In addition, about 70 % of the total time is wasted in the transportation of products between machines and in the excess motion of workers. Furthermore, WIP efficiency is 32 %. There was an average of 200 pieces under processing in one shift while the target is about 63. Also, the indicator shows that the company has good throughput efficiency which is 94 %. Finally, the quality efficiency is indicated by the metric about 20 %.

Process Variability

The variability of the process is very high, about 88 %. There is a high fluctuation in stage five, six, and seven. One reason for such variation is the existence of many raw material entrance points to the line which cause unscheduled and non-orderly production. In addition, cycle time variation due to worker capability and machine reliability contribute to that variation.

Process Flow

The metric indicates that the flow efficiency is medium. Five inter-stage flows were continuous, where four were having push flow, and only one used pull flow. It was noted that several buffers existed in the push inter-stage flow locations due to variation in cycle time (e.g. cycle time for the fourth stage is 7.5 min while for the following stage, fifth stage, is 4 min). This is a clear example of how the selected parameters of the EFV are inter-related to one another.

4.4. Suggested Lean Solutions in Light of the EFV Metric Results

Several suggested lean solutions were proposed to improve the plant process and increase the leanness level. The company in currently in the process of implementing several of the suggested initiatives to increase its leanness level up to 10% on the developed EFV metric scale. Examples of the suggested lean solutions are as follows:

- Increasing the value added time by decreasing the lead time of the production process. Kaizen focused group can be dedicated for such task.
- Improving the efficiency of the mills using standardization and total productive maintenance (TPM) techniques.
- Applying single minute exchange of die (SMED) technique will reduce the wasted time due to changeover.
- Using the Heijunka box principle (production leveing tool) in order to balance cycle time in the processes. Balanced cycle time in the process will reduce the probability of having bottleneck(s) and reduce variation.
- Applying “7 whys” approach to solve the root causes of the process quality problems.
- Increasing the automation level of certain stages in the plant will speed up the processes and reduce cycle time. For example, using a robot that has eye fish (360°) and a camera to inspect the inside of a pipe during the internal inspection (ID) stage will reduce inspection time and improve inspection quality.

V. CONCLUSION

This paper presented an approach for lean assessment quantification. Transforming to a lean manufacturing should always be accompanied with how to assess and track such transformation. Efficiency, type of flow and variability have been integrated in the developed metric (EFV) to measure the leanness level in a manufacturing system. The three parameters assist for the first time in measuring the system performance, system stability, and flow smoothness. Each one of these parameters plays an important role in enhancing system leanness level. Integrating these three parameters in one metric gives the lean practitioners a clear picture of how lean the system is. A performance range for the expected values of the developed EFV metric was presented as a visual approach to see and track the system leanness level and its improvement during the lean journey.

The presented case study illustrated the practical impact of the developed metric and assessment approach. Each parameter of the EFV metric measured an important leanness perspective in determining entire process leanness level. The results of leanness assessment in the case study pointed to various areas of improvements in the facility leading to different focused lean initiatives and plans.

The developed EFV metric will enhance the existing leanness measurement literature, help manufacturing managers and practitioners to measure the lean level of their organization, and finally assist in tracking lean initiatives impact. Future work will include exploring the integration of other leanness parameters, incorporation more variation aspects, and finally applying the developed EFV metric to service industry.

APPENDIX A

TABLE A1. PROCESS DATA

Item	Data
n(maximum no of machines in stages)	4
m (no of stages)	11
$\sum_{i=1}^{11}\sum_{j=1}^{4} v_t$	79.5 min
$\sum_{i=1}^{m} \mathrm{I_m}$	72 min
$\sum_{j=1}^{n}\sum_{i=1}^{m} \mathrm{I_w}$	60 min
$\sum_{i=1}^{4} M_w$	263.5 min
$\sum_{i=1}^{m} M_p$	245 min
$\sum_{j=1}^{n}\sum_{i=1}^{m} TH^{\circ}$	0.8 p/min
$\sum_{j=1}^{n}\sum_{i=1}^{m} WIP$	200 p
$\sum_{i=1}^{11}\sum_{j=1}^{4} Th$	100 p
$\sum_{i=1}^{11}\sum_{j=1}^{4} D$	106 p
$\sum_{m=1}^{11}\sum_{n=1}^{4} parts\ with\ no\ defects$	35 p
$\sum_{m=1}^{11}\sum_{n=1}^{4} parts\ with\ no\ defects + \sum_{m=1}^{11}\sum_{n=1}^{4} parts\ with\ defect$	175 p

TABLE A2. TIME MEAN AND STANDARD DEVIATION OF PROCESSES

Process	Mean	Standard Deviation
Pipe Making	5	0.2
Pipe Cleaning	6.5	0.3
Preliminary Sonic Inspection	7.5	0.7
Internal Inspection	4	0.2
Outside Inspection	4	0.6
X-ray Inspection	5	0.5
Final Finishing	4	0.4
Final Visual Inspection	8.5	0.7
Final Sonic Inspection	7	0.6
Scale	15	0.8
Customer Inspection	5	0.3
Burn Bay and Real Time	40	0.9

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