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Improving the efficacy of the lean index through the quantification of qualitative lean metrics.

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Abstract

Multiple lean metrics representing performance for various aspects of lean can be consolidated into one holistic measure for lean, called the lean index, of which there are two types. In this article it was established that the qualitative based lean index are subjective while the quantitative types lack scope. Subsequently, an appraisal is done on techniques for quantifying qualitative lean metrics so that the lean index is a hybrid of both, increasing the confidence in the information derived using the lean index. This ensures every detail of lean within a system is quantified, allowing daily tracking of lean. The techniques are demonstrated in a print packaging manufacturing case.

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Keywords: *Lean metirc; lean performace; lean index; qualitative analysis; quantitative analysis*

1. Introduction

Lean manufacturing (LM) involves all practices, activities, tools, methods and techniques intended to reduce and even eliminate waste within organizations. Just in Time, Quality Management, Continuous Improvement, Single Minute Exchange of Die, Total Productive Maintenance, Kaizen and many other practices and methods are typically identified with LM.

Researchers have focused much effort on how best to derive maximum benefits from LM, and so lean metrics have been established as the primary means of tracking the success and implementation of LM. As there are practices, so also are lean metrics and there is an abundance of both. Using one or a set of lean metrics needs to be weighed against using another set. In addition, LM is a philosophy and not concrete objects [1], so by nature its performance assessment needs to be qualitative. But quantitative lean metrics are also used to track LM performance, and this creates another dilemma between choosing either qualitative or quantitative lean metrics to track lean performance. Qualitative lean metrics are the lean performance indicators that are measured using natural everyday language or expressions. For example scoring the performance of Management Commitment to lean initiatives or the prevalence of Standard Operating Procedures cannot be precisely quantified; rather they are rated with phrases like "very high" or "average". On the other hand, quantitative lean metrics in their original form are measured with numbers. For example defect rate can be measured precisely to the nearest percentage, say 10%. Also average set-up time in a plant can be computed to the nearest minute, for example 12 minutes.

Lean assessment frameworks are used to develop an overall performance map in order to identify areas of improvement and track the overall success and implementation of LM. The frameworks being referred to in this article are those that are used to assess multiple aspects of lean. Frameworks like the European Foundation for Quality Management (EFQM) are excluded from this list as they focus on specific lean aspects (quality in this case), even though they are used in lean assessment. Table 1 comprises various qualitative and quantitative based lean assessments that have been extracted from a background investigation. A literature search for hybrids, i.e. lean assessment frameworks

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that are simultaneously qualitative and quantitative, showed a void.

A lean assessment framework that has both qualitative and quantitative expressions is the lean index (LI). Benchmarking has this merit, but the LI also has benchmarking capabilities [2,3]. The LI for lean performance assessment is a weighted summation of the lean metrics that define performance of various variables representing lean practices within the system. These lean metrics are either qualitative or quantitative types as described earlier and determine if the LI is qualitative or quantitative based. The LI is as comprehensive as the lean metrics used in deriving it [4]. Using more lean metrics within the LI model improves the comprehensiveness of the final LI [4].

Table 1. Various frameworks that have been used for qualitative and quantitative lean assessments.

	Qualitative frameworks	Quantitative frameworks
Model	Lean self-assessment tool (LESAT) [5], Qualitative lean index [6-13], Balanced Scorecard [14], Benchmarking [15], Strategos LAT [9]	Value Stream Mapping [17], Mahalonibis Taguchi Gram Schmidt, System [18], Quantitative lean index [2,3, 19-21], Benchmarking [2,3]
Strengths	Lean metrics are easy to develop, apply and analyse. Qualitative lean metrics can be generated for most lean aspects and this improves the scope of the assessment. The use of every-day linguistic terms such as "high" of "low" to rate performance makes them easy to administer.	Allows lean performance to be mapped and tracked objectively and more regularly. The lean metrics can be statistically analysed. Quantitative lean assessments enable modelling analysis such as simulation.
Weaknesses	Self-assessment ratings are open to bias. Qualitative lean metrics cannot be analysed statistically. They do not enable routine example daily, assessments. Linguistic characterizations, which are less specific than numerical ones [16]. It is also less precise and therefore less informative [16].	Quantitative data are not always easy to collect. Not all lean aspects can be measured with quantitative lean metrics so this limits the scope of the assessment

The LI like other lean assessment frameworks is either qualitative or quantitative; considering the strengths and weaknesses identified in Table 1, it shows that it is better to have hybrid lean assessment frameworks so that the limitations of either are cancelled out. One possible way of achieving a hybrid is to quantify qualitative lean metrics.

There are various methods commonly used to quantify qualitative lean metrics, but these have not been appraised in the extant literature on lean assessment. A study to highlight the various methods, their strengths and limitations and their typical applications is required. The benefit of such a study will bridge the divide between qualitative and quantitative lean metrics, so that both can be converged seamlessly into a single lean assessment framework when the need arises. Accordingly this article is structured as follows: section two reviews the lean assessment efficacy of qualitative and quantitative LI frameworks to justify the need for the present work; section three describes and critiques existing methods of quantifying qualitative lean metrics; in section four the methods are applied to a print packaging manufacturing case; while section five discusses the academic and industrial implications of the study.

Nomenclature

AHP	analytical hierarchy process
ANP	analytical network process
DEA	data envelopment analysis
FA	factor analysis
FL	fuzzy logic
JIT	just in time
KPI	key performance indicator
LAT	lean assessment tool
LESAT	lean enterprise self-assessment tool
LI	lean index
LM	lean manufacturing
QM	quality management
SMED	single minute exchange of die
SOP	standard operating procedure
WIP	works in process

2. Literature review: lean index for lean performance assessment

For clarity sake, the LI for lean performance assessment is synonymous with the models, methods and frameworks to consolidate multiple lean metrics into one holistic measure or score for lean. When expressed in percentage terms, the LI identifies the gap between current state and the ideal lean target. It shows how aligned the organizational behavior is towards sustaining lean transformation [11]. It allows lean assessment to align with company objectives [3,19] and competitive strategies [2]. Since the LI is an amalgamation of the lean performances for various aspects of lean, the methods used in computing the LI highlight weak and strong areas of lean [6-8]. For example low scores represent lean practices that have not yet been implemented or have been implemented sparingly, while high scores represent successes with the lean practice. It has been used to show the variables that contribute the least or the most to organizational leanness [3]. All these benefits render the LI useful in lean assessment frameworks.

2.1. Qualitative lean index

The qualitative based LI relies solely on qualitative lean metrics, and the basic form is the lean self-assessment tool or questionnaire. In the approach, experts who are familiar with lean in the organization rate the performance of different aspects of lean within the organization. A Likert type scale or linguistic expressions are the established means for rating purposes. A linguistic variable, as the name suggests, is a variable whose value is expressed in words or phrases using natural language [16]. For example Taj et al [9] measured how easy it was to shift output when the product mix changes; they measured this on a scale of zero to four using the linguistic terms- “Very difficult”, “Moderately difficult” and “Easy”. In this case the qualitative lean metric is process flexibility. Zanjirchi et al. [10] measured the performance rating of the prevalence of pull production; they used the linguistic variables- “Worst”, “Very poor”, “Poor”, “Fair”, “Good”, “Very good” and “Excellent”.

Within the assessments using qualitative based LI, the inclusion of qualitative lean metrics is varied. As many as thirty lean metrics representing five aspects of lean have been included in the lean assessment [6-8, 16], and as much as forty were used to assess nine areas of lean [9], see Table 2. This is evidence that the qualitative based LI has been used to cover a wide scope of lean aspects within a single assessment.

Table 2. Various qualitative based LI

Ref No.	Approach and methods	Number of lean metrics used	Examples of lean metrics used
[15]	FL, if-then rules	30/5[1]	Prevalence of continuous improvement culture. Usage of TQM tools. Implementation of job rotation system.
[16]	FL, ANN	30/5	Employee involvement. JIT flow.
[17]	FL	30/5	Implementation of Poka-Yoke. Standardization of components.
[18]	Spreadsheet based self-assessment tool	40/9	Characterization of material movement. Appearance of plant.
[19]	FL	54/10	Suppliers deliver to plant on JIT basis. Use of Kanban squares for production control.
[20]	ANP	12/4	Employees work attitude. Communication.
[21]	DSS, FL	30/5	Employee empowerment. Employee spirit and cooperation.

[1]Thirty qualitative lean metrics representing performance for five different aspects of LM.

The benefits and limitations of using qualitative lean assessment frameworks have been highlighted in Table 1, and these extend to the qualitative based LI. However there are some benefits that are worthy of mention. The use of multiple responses from various experts who know about lean in the organization helps to minimize the drawbacks of subjective responses [7,8,11]. The performance rating assigned by each individual is weighed, aggregated and finally averaged to improve confidence in the LI [7,8,10,11]. The use of modeling algorithms such as FL and ANN helps to improve the preciseness of the LI.

Another benefit is that the final qualitative LI is a quantifiable number which can be mapped for Visual Management and tracking of lean performance. Taj et al [9] used a radar and bar chart to represent lean performances. Although the final output of the qualitative based LI is a number, the fact remains that the performance values for the lean metrics were obtained subjectively.

2.2. Quantitative lean index

Aside from incorporating quantitative lean metrics, the basic form of the quantitative LI is mathematical modeling [see 2,3,19-21].

Table 3. Various quantitative based LI

Ref No.	Approach and methods	Number of lean metrics used	Examples of lean metrics used
[2]	DEA	3/3[1]	Cost, Time, Product value
[3]	FA	8/2	Inventory turnover, throughput, energy consumption
[19]	AHP	5/5	First-time-through (FTT) capability. Dock-to-dock (DTD) days
[20]	FL	8/2	Scrap rate, non-value added time, set-up time, average lead time, number of orders delivered late
[21]	FL	62/8	Overall Equipment Effectiveness (OEE), Cycle time, Stock turnover rate

[1]Three quantitative lean metrics representing performance for three different aspects of LM

Within the extant literature on quantitative LI, the inclusion of quantitative lean metrics is twofold. Generic Key Performance Indicators (KPIs) such as FTT capability, DTD days, OEE, throughput and defect rates have been used, see Table 3. Non-generic and specific lean metrics have also been formulated and included in the analysis such as total transportation cost as a ratio of total annual sales [20] and number of parts transported as a ratio of total sales [21].

The number of lean metrics included in the quantitative LI is disparate; on the average, few are used (Table 3). It is essential to choose few and an efficient number of lean metrics that best evaluate lean for the system [1,19,20], but by using few lean metrics other important areas are left out of the analysis. Pakdil and Leonard [21] have used many quantitative lean metrics in their analysis of multiple aspects of LM. However, their quantitative lean metrics are limited to aspects of LM performance that can be quantified, excluding other areas like Training, Management Commitment and Visual Management.

Like their qualitative counterparts, the quantitative LI exhibit generic strengths and limitations of quantitative lean assessment frameworks already identified in Table 1. However the quantitative based LI offer some uniqueness that is remarkable. The quantitative LI can be used as a benchmarking lean metric for a specific industry and also as a benchmarking tool for internal organizational operations by indicating which organizations or operations are leaner than others [3]. The mathematical modeling foundation of the quantitative LI is a bonus, as it enables simulation. Ray et al.

[3] experimented with their LI model by first estimating the likely impact of various improvements on each lean metric in the model. They then plugged these estimated improvements in lean metrics into the LI model, and observed how the particular improvement changed the overall and operation-by-operation lean performance.

2.3. Section summary

An attempt to model both quantitative and qualitative lean metrics within a single lean assessment framework was made by Pakdil and Leonard [21]. In their work one Fuzzy Logic (FL) based LI was used for the qualitative aspects of LM while another FL based LI was derived for the quantitative aspects. Fundamentally, a LI is either purely quantitative or exclusively qualitative, and this is equally evident in lean assessment tools and frameworks. There are key benefits attached to each type: so why not have both under one unified framework? But before this can be achieved we need a means of quantifying qualitative lean metrics.

3. Approaches to quantifying qualitative lean metrics

A phenomenon is well understood if it can be characterized in quantitative terms [16]. With this notion in mind the effort then should be geared towards quantifying qualitative lean metrics, since quantitative lean metrics are already expressed in numbers.

3.1. Fuzzy numbering

Researchers have perfected an old-age methodology of quantifying qualitative data by assigning numerical values to different reference points on a datum that represents the scale of the linguistic measurement in a performance metric (e.g. Fig. 1).

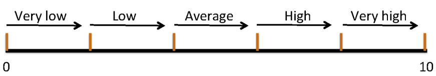

Fig.1. Linguistic variables used in describing lean performance

Impreciseness arises in assigning a numerical value to represent “very low” performance for example, but by allocating fuzzy numbers to each linguistic description of performance, the problem of vagueness is overcome.

The basic concept behind using fuzzy numbers in quantifying linguistic variables is the Fuzzy set theory, which states that elements with un-sharp, non-crisp boundaries are defined by a class that has a continuum of grades of membership [22,23]. Fuzzy set A in a universe of discourse X is characterized by,

$$A = \{(x, \mu A (x))|x \in A, \mu A (x) \in [0,1]\} \quad (1)$$

where μA (x) is the fuzzy membership function, which defines the degree to which x belongs to A and associates with each element x in X, a real number in the interval [0,1] [21].

Triangular and trapezoidal fuzzy sets are the most familiar types of fuzzy set operations due to their simplicity and sufficiency in most analysis. Table 4 is an example of fuzzy numbers applied to the linguistic variable of Fig. 1, and depicted graphically in Fig. 2.

Table 4. Fuzzy numbers selected for approximating linguistic performance variables.

Linguistic variable	Fuzzy numbers (using triangular membership area)
Very low	0, 1.5, 3
Low	2, 3.5, 5
Average	4, 5.5, 7
High	6, 7, 8
Very high	7.5, 9, 10

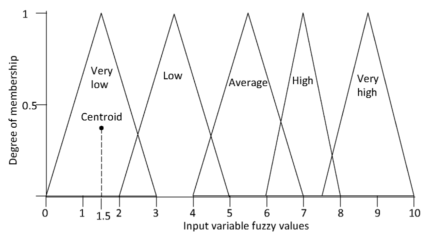

Fig. 2. Fuzzy membership area for linguistic variable

The fuzzy numbers need to be converted back (defuzzified) to crisp numbers to make meaning. For defuzzifying fuzzy numbers a variety of methods are available such as the centroid or center of area method, maximum membership principle and fuzzy mean method. The centroid method is simple and is commonly used. For a triangle the centroid calculation is a straightforward computation, for example “very low” performance has a crisp defuzzyfied value of 1.5 (see Fig. 2). If the scale is made proportionate to represent between 0% and 100%, the value of 1.5 can be taken as 15%. References [6-8,10,12,13] contain detailed descriptions of how fuzzy numbers were used within lean assessment settings.

The fuzzy numbering approach is simple and well established within the literature. To minimize the effect of bias in the responses given by those who fill out the self-assessment questionnaire, multiple responses are obtained from different respondents.

Fuzzy numbering is practicable in lean assessments that require periodic say quarterly or yearly data inputs, as it will not be pragmatic to collect subjective information on a daily or routine basis. Also the values of the lean metrics have been obtained subjectively.

3.2. Bespoke lean metrics

Another method of quantifying qualitative lean performance variables is to use bespoke and specifically formulated metrics. Examples and references are given in Table 5. The strength of this method lies in its bespoke nature, which allows specific information to be derived from the lean assessment, however expert knowledge of the situation is required.

Table 5. Referenced literature on bespoke quantitative lean metrics defined for qualitative variables.

Ref. No.	Lean aspect	Bespoke lean metric
[21].	QM	Percentage of inspection carried out by autonomous defect control devices. Total number of people dedicated primarily to quality control ÷ total employees.
[24].	Elimination of waste	Percentage of common parts in company products.
	JIT	Number of times and distance parts are transported.
[25].	Visual factory-industrial housekeeping.	Percentage of the plant where there are lines on the floor to distinguish work areas, corridors, etc.
	Multi-function employees	Percentage of production operatives that have received structured training for the different work positions.

3.3. Surrogate lean metrics

Eliminating subjectivity that comes with using the FL approach may be essential in an assessment, and at the same time bespoke metrics may not be easily defined for a qualitative lean performance variable. The third option, using a surrogate metric, would be appropriate and this is common in LM performance measurement systems [1].

A surrogate acts as proxy to the actual lean performance variable. Table 6 includes some examples found in the extant literature.

Table 6. Referenced literature on surrogate quantitative lean metrics defined for qualitative variables.

Ref. No.	Lean aspect	Surrogate lean metric
[1].	JIT	Inventory levels
	Kaizen	Relative change in inventories over time Long-run change in cost of good sold percentage of sales
	QM	Relative change in market share for cars, trucks and combines products of cars and truck
[3].	Employee commitment and involvement	Employee efficiency Safety performance
	Management commitment and training	Plant utilization Return on investment
	Space utilization	Sales turnover per sq. ft.
	Customer satisfaction	Price reduction history
	Supplier relationship	Procurement cost

By using surrogate lean metrics, the lean assessment enables everything to be measured thereby increasing confidence in the outputs from the assessment. However surrogates are not direct measures; a convincing argument for using it will need to be communicated. It is also common to use data that is obtained from year-end financial reports, but such data are significantly historical and hardly mirror current performance.

4. Application of methods in print packaging manufacturing case study

The selected case is a flexible print packaging manufacturer. The company has set out to apply the LI framework in its manufacturing plant, and requires one lean assessment framework that is all encompassing of both qualitative and quantitative aspects of lean. LM performance is to be tracked using daily lean performance data.

Table 7 comprises the list of lean aspects and the quantitative lean metrics defined for each of them. A mixture of generic (commonly used), bespoke and surrogate lean metrics have been defined for each one and standardized to minimize bias due to scale. The values in column 3 of Table 7 are the actual recorded performances for each lean aspect for one production shift. For the scope of the present article only one lean metric has been defined for each lean aspect although multiple ones may be defined.

Table 7. Quantitative lean metrics defined for a LI framework that has both qualitative and quantitative variables.

Lean aspect	Description of lean metric	Recorded values for a single assessment
Cleanliness[1]	Number of cleaning activities undertaken as a ratio of total scheduled cleaning activities[2]	0.73
Work place house keeping[1]	Percentage of tools and materials arranged on shelves and properly labeled[2]	20%
SMED	Average set-up time[3]	22 minutes
Lot size reduction	Average production run time between set-ups[3]	93 minutes
JIT Management	Average manufacturing lead time ÷ current manufacturing demand[3]	0.0017 days/kg
Kaizen	Number of new suggestions that get implemented ÷ total number of suggestions[3]	0
Leadership commitment[1]	Average per unit manufacturing cost[4]	£0.0015
Multi-skilled Workforce[1]	Percentage of staff that completed three or more inter-departmental activities[4]	18%
QM	Manufacturing defect rate[3]	9%
Safety	Number of work related injuries or near misses[2]	1
Scheduling	Percentage of jobs produced to schedule[3]	32%
TPM	Mean time to machine breakdown[3]	67 minutes
Team work[1]	Percentage of jobs completed by teams[2]	13%
Standards[1]	Number of major activities completed late due to activity related errors ÷ total number of major activities[4]	0.23

[1]qualitative lean aspect; [2]bepoke lean metrics; [3]generic lean metric; [4]surrogate lean metric

Table 7. Contd.

Lean aspect	Description of lean metric	Recorded values for a single assessment
Training[1]	Number of new and ÷ or improved activities as a ratio of total number of activities[4]	0.007
Waste Elimination	Total machine idle time ÷ total scheduled machine run time[4]	0.09
WIP reduction	Average wait time for parts to be processed ÷ current manufacturing demand[2]	0.02 minutes/kg
Workforce commitment[1]	Average efficiency of machine operators i.e. actual output as a percentage of target[4]	64%

[1]qualitative lean aspect; [2]bepoke lean metrics; [3]surrogate lean metric; [4]generic lean metric

5. Discussion and conclusion

The quantified values in column 3 of Table 7 are of greater significance when assessed in relation to reference target (ideal case) and baseline (minimum allowable) lean performances for each lean metric. For example if a baseline of 50% is set for Workforce Commitment, then the actual performance of 64% is an indication that the lean aspect has achieved only 28% of a target value of 100%. The plant needs to improve the commitment of its shop floor workers to lean practices by as much as 72%. Other lean aspects can be assessed in a similar manner. A common practice is to assign subjective performance ratings (through Likert scales or linguistic terms) to the qualitative lean aspects [for example 8,9]. The quantified qualitative lean metrics eliminates subjectivity in the lean assessment for the plant and enables the quantification of improvement efforts.

Manufacturing leanness measurement is a multi-criteria decision making problem [7] and requires the use of multiple lean metrics [1,2]. In short no single measure can be used to indicate the leanness level of the system. The values in column 3 of Table 7 become the lean metrics (inputs) for a LI model, enabling the LI to simultaneously assess both the qualitative and quantitative lean aspects for the manufacturing case. The LI output becomes a more comprehensive and less subjective leanness measure than when using either qualitative or quantitative lean metrics alone. Any of the LI models identified in Table 3 become candidates for a hybrid (jointly qualitative and quantitative) lean assessment framework: the computation of the leanness level of the system using a LI model is beyond the scope of this article.

The academic implications of this study point towards the development of hybrid lean assessment frameworks. These hybrids will overcome the weaknesses of each type (qualitative and quantitative) and take advantage of their individual strengths. The Strategos LAT applies both qualitative and quantitative lean metrics, but the former are assessed subjectively with both linguistic terms and Likert-type scales [9]. By using the approaches described for this article, the subjective responses obtained using the Strategos LAT, LESAT and other qualitative lean assessments, can be verified objectively, strengthening the confidence in the information from the assessment.

References

[1] Bayou ME, de Korvin A. Measuring the leanness of manufacturing systems- a case study of Ford Motor Company and General Motors. J Eng Technol Manage 2008;25:287-304.
[2] Wan H and Chen FF. A leanness measure of manufacturing systems for quantifying impacts of lean initiatives. Int J Prod Res 2008;46:6567–6584
[3] Ray CD, Zuo X, Micheal JH and Wiedenbeck JK. The lean index: operational lean metrics for the wood products industry. Wood and Fiber Sc 2006;38:238-255
[4] Oleghe O and Salonitis K. A comparative analysis of quantitative lean index models. Submitted to Int J Prod Perf Manage 2015.
[5] Nightingale DJ and Mize JH. Development of a lean enterprise transformation maturity model. Info Knowledge Sys Manage 2002;3:15-30
[6] Vimal KE and Vinodh S. Leanness evaluation using if-then rules." Int J Adv Manuf Technol 2012;63:407-413.
[7] Vimal KE., Vinodh S. "Application of artificial neural network for fuzzy logic based leanness assessment." J Manuf Technol Manage 2013;24:274-292
[8] Vinodh S and Vimal K. Thirty criteria based leanness assessment using fuzzy logic approach. Int. J. Adv. Manuf. Technol 2012;60:1185-1195
[9] Taj S. Applying lean assessment tools in Chinese hi-tech industries. Management Decision 2005;43:628-643
[10] Zanjirchi SM, Tooranlo HS and Nejad LZ. Measuring organizational leanness using fuzzy approach. Proceedings of the 2010 International Conference on Industrial Engineering and Operations Management. Dhaka, Bangladesh. January 9-10, 2010
[11] Wong WP, Ignatius J and Soh KL. What is the leanness level of your organisation in lean transformation implementation? An integrated lean index using ANP approach. Production Planning & Control 2014;25: 273–287
[12] Vinodh S and Balaji SR. Fuzzy logic based leanness assessment and its decision support system. Int J Prod Res 2011:13: 4027-4041
[13] Singh B, Garg SK and Sharma SK. Development of index for measuring leanness: study of an Indian auto component industry. Measuring Business Excellence 2010;14: 46-53.
[14] Seyedhosseini SM, Taleghani AE, Baksha A, Partovi S. Extracting leanness criteria by employing the concept of balanced scorecard. Expert Sys. Appl. 2011;38:10454-10461
[15] Gurumurthy A, Kodali R. Application of benchmarking for assessing the lean manufacturing implementation. Bench.: Int. J. 2009;16:274-308.
[16] Zadeh LA. The concept of a linguistic variable and its application to approximate reasoning. Information and Control 1975;8:199-249.
[17] Abdulmalek FA and Rajgopal J. Analyzing the benefits of lean manufacturing and value stream mapping via simulation: a process sector case study. Int J Prod Econs 2007;107:223-236.
[18] Srinivasaraghavan J and Allada V. Application of mahalanobis distance as a lean assessment metric. Int J Adv Manuf Technol 2006;29:1159–1168
[19] Searcy DL. Developing a lean performance score. Strategic Finance 2009;Sept:34-39
[20] Behrouzi F and Wong KY. Lean performance evaluation of manufacturing systems: a dynamic and innovative approach. Procedia Computer Science 2011;3:388-395
[21] Pakdil F and Leonard KM. 2014. Criteria for a lean organization: development of a lean assessment tool. Int J Prod Res 2014;52:4589-4607
[22] Zadeh LA. Fuzzy sets. Information and Control 1965;8:338-353.
[23] Zadeh LA. Fuzzy algorithms. Information and Control 1968;12:94-102.
[24] Sanchez AM and Perez MP. Lean indicators and manufacturing strategies. Int. J. Ops. Prod. Manage 2001;11:1433-1451
[25] Bonovia T and Marin JA. An empirical study of lean production in the ceramic tile industry in Spain. Int. J Prod. Ops. Manage 2006;26:505-531, 2006