Int J Adv Manuf Technol (2016) 83:1171–1188
DOI 10.1007/s00170-015-7513-4

ORIGINAL ARTICLE

Development of a lean maturity model for operational level planning

Mohammad Ali Maasouman[1] · Kudret Demirli[1,2]

Received: 1 January 2015 / Accepted: 29 June 2015 / Published online: 7 August 2015

Abstract In this paper, a visual, data-driven operational level lean maturity model is developed. The model can be used to assess level of lean maturity and to compare it to performance results in different axes of manufacturing cells in order to evaluate lean effectiveness. As demonstrated in this paper, to measure effectiveness of lean manufacturing, both inputs (tools and processes) and outputs (performance) are measured separately and analyzed together. A case study is carried out for gathering data, analysis, and explanatory study of results. Qualitative and quantitative data on lean capability and performance of two manufacturing cells is collected using historical data and audit. A scoring system based on the major and minor non-conformances is suggested to quantify the indicators of leanness. Minimum of fuzzy membership values is selected to calculate overall performance. Then, the results of leanness are compared with performance to highlight the gaps of lean effectiveness. Results of the study show that the developed model can be used to measure both leanness and lean effectiveness through assessment of lean performance. The model can be applied by practitioners as a framework to design and develop a company-specific lean maturity model.

Keywords Lean manufacturing · Leanness assessment · Maturity model · Organizational performance · Production cell · Fuzzy sets

✉ Kudret Demirli
kudret.demirli@kustar.ac.ae

[1] Department of Mechanical & Industrial Engineering, Concordia University, Montreal, Canada

[2] Department of Industrial & Systems Engineering, Khalifa University, PO Box 127788, Abu Dhabi, UAE

1 Introduction

Over the last three decades, there has been a growing focus on development and implementation of improvement techniques such as lean and Six Sigma. Lean manufacturing based on the Toyota Production System (TPS) is a set of principles, tools, and methods that form a management philosophy where value is defined as what customer is willing to pay for [1]. Based on a survey conducted by Process Excellence Network (PEX) in 2013, lean and Six Sigma remain the most widely methodologies of process improvement [2]. Diverse maturity models and assessment tools have been developed for lean evolution [3]. Most of the maturity models provide a general direction and a company-wide roadmap. Despite importance role of manufacturing cells (MCs) in creating value, transformation principles to respond to the change requirements in the operational level have not been considered as deserved.

On the other hand, in some studies, lean is measured against presence of evidence on application of lean tools and principles [3–6]. These models are quite technique-oriented. Consequently, they fail to monitor the effectiveness of lean practices. Another group of studies have concentrated on performance measurement as a result of lean initiatives [7–9]. Although these studies provide a good indication of lean effectiveness, they do not provide adequate visibilities on the weaknesses in the implementation of system.

In summary, in existing lean assessment models, neither the leanness measures in MCs nor the relationship between daily activities related to lean implementation in MCs and their performance are considered properly. Both types of assessment models mentioned above also failed to provide a visual presentation of leanness and performance easy to understand by all levels of organization. Furthermore, most of the proposed models have been developed from an assessment viewpoint, as would be conducted by the third parties. In each organization, it is necessary to develop a self-assessment model in order to assess lean efforts. Considering the aforementioned void within the body of knowledge and practical initiatives, by developing a dynamic, multi-dimensional lean maturity model (LMM) customized for operational level, this research seeks to address the following fundamental questions:

1 How can an organization measure overall leanness and lean maturity level of a production cell? Which quantitative and qualitative metrics should be used?
2 How can an organization measure the overall performance of a production cell?
3 How can an organization evaluate effectiveness of its lean practices in production cells?
4 How can a multi-dimensional maturity model support an organization to assess its overall lean performance?

In this study, leanness refers to the maturity level of lean which is measured by assessing the implementation of lean tools and principles with respect to adapted maturity levels. Lean effectiveness, on the other hand, represents the impact of lean on achievement of manufacturing performance objectives by comparing the leanness with the extent the objectives are met. This analysis in general has been called as assessment of lean performance.

Since there is no one-best-way recipe for lean implementation [10], this study does not intend to provide a detailed prescription for MCs. However, it proposes a framework to assess lean maturity based on grounded lean manufacturing principles. It also suggests a dynamic process to adopt designed framework according to firm's strategies and priorities. Furthermore, by measuring the performance of MCs from different perspectives and then comparing them with the results of lean assessment in each dimension, as suggested in this study, the model can be used to evaluate effectiveness of lean initiatives. The visual format of lean LMM can be applied to find the gaps between requirements of leanness and results of their practices, and to fill that gap through focusing on the areas of strength and those requiring improvement.

2 Literature review

2.1 Lean history

Among all attentions to Japanese management system, Toyota Production way has drawn the widest consideration [11]. In 1978, Ohno published "Toyota Production System" in Japan and credited Ford Production System and American supermarkets behind his just-in-time thinking [12]. Shingo and Dillon [13] described the principles and mechanics of Toyota Production System such as Just-in-time, elimination of wastes, SMED, and Kanban. Toyota shop floor management was later called lean by John Krafcik in 1988 [1]. Based on the series of research started by Spear and Bowen [14], more attention has turned to rules and principles of lean manufacturing, the nature of working that has been called "DNA of TPS". The concept of lean manufacturing has been evaluated and expanded significantly beyond its origins in the automotive industry [15]. Today, lean principles have being applied in all sectors of manufacturing, banking, healthcare, and even non-profit organizations.

2.2 Lean maturity and assessment models

Recent literature shows an increasing interest in maturity models [16]. Using a maturity model to define directions, prioritizing improvement opportunities and guide cultural changes is a helpful way of managing the major transformation changes [17]. Lean is a gradual process of deep-rooted change in the organizational culture. Therefore, a maturity model is crucial for achieving a sustainable lean status. The lean measurement approaches can be divided into two main groups: qualitative and quantitative [18].

2.2.1 Qualitative assessment

Different levels of maturity have been proposed for lean implementation and lean assessment. The conceptual definitions of maturity phases are analyzed from different perspectives during development of LMM in order to design an appropriate model of leanness for production cells in this study. In the operational level, for example, "Renault Production System (RPS)" was developed by Renault Company based on the Nissan Production way. RPS rules, procedures, and techniques are applied to increase industrial performance in four main manufacturing functions, namely product and process design, inbound supplying, outbound logistics, and manufacturing [19].

In enterprise level, Lean Enterprise Self-assessment Tool (LESAT) was developed by Lean Aerospace Initiative (LAI) at the Massachusetts Institute of Technology. Among all the developed models of lean management, LAI provided one of the most comprehensive ones in which the primary activities and major tasks as well as supportive enablers and tools have been described. Although LAI's framework is one of the most comprehensive models of lean transition, like many other recent lean manufacturing models, it concentrates on internal and external relations and strategic implementation of lean from the enterprise perspective.

The Shingo Prize, as another widely used lean assessment models, was created in 1988 at Jon M. Huntsman School of Business at Utah State University. Shingo model maintains systematic lean assessment through considering the organization culture as a key driver of lean implementation [20]. In Shingo model, too much attention has been spent on principles as the fundamental elements of organization culture and key drivers of business excellence. While Shingo model can be used as a comprehensive guideline of cultural change in all level of organization, a complementary model of lean assessment based on the tangible evidences and quantitative criteria seems necessary.

2.2.2 Quantitative assessment

In the second groups of assessments, performance outputs have been used as the result of lean implementation to assess the leanness. Wan and Chen [21], for instance, proposed data envelopment analysis (DEA)-leanness as a single index of leanness level. Fuzzy logic concept has been applied by some other researchers to assess leanness of organization (Singh et al. [22], Vinodh and Vimal [23], Vinodh and Chintha [24], Zanjirchi et al. [25], Anvari et al. [7]). More recently, Behrouzi and Wong [18] proposed an integrated stochastic-fuzzy modeling approach to evaluate leanness of supply chain. They used expert's judgment to extract the 28 lean supply chain performance measures from an initial list and to score them using data gathered from a survey.

Although each of the abovementioned models provides insights into the level of lean maturity to some extent, none of them presents a visual link between the level of lean maturity in MCs and effectiveness of lean implementations in achievement of manufacturing cell's objectives. This study addresses the both aspects of the lean equation, leanness and lean effectiveness.

3 Methodology

The main purpose of this study is to develop a lean maturity model adapted to the specifications of MCs. Thus, focus is on descriptive analysis and explaining relationships and outcomes [26]. The units of analysis are MCs of a manufacturing company. The main lean control items and performance metrics are the elements of analysis. A conceptual model is developed based on the review of literature. Suggested model provides the basis for deciding on the type of data to be gathered. Next, a case study approach is used to collect data of analysis. Lean maturity is investigated within its real-life context [26] through analysis of both quantitative and qualitative data collected from two MCs. Then, data is analyzed inductively. Further analysis of data enhances the developed theoretical framework by interpreting leanness and performance results and developing overall measurements. Figure 1 shows the general framework of the research methodology.

3.1 Design phase

Study of existing qualitative and quantitative lean assessment models provides inputs on two important aspects of proposed LMM. On the one hand, assessing the quality of lean implementation based on customized model of lean provides direction and consistency to a lean implementation by emphasizing standardization. Renault Production System is used as a model of lean implementation in manufacturing cells in this concept. On the other hand, fuzzy logic concept is used as an appropriate technique to deal with multiple indicators of lean effectiveness in a complex manufacturing environment. By applying these two important findings from analysis of existing qualitative and quantitative lean assessment models, a conceptual framework is developed and tailored to the requirements of workstations at the operational level in following three steps:

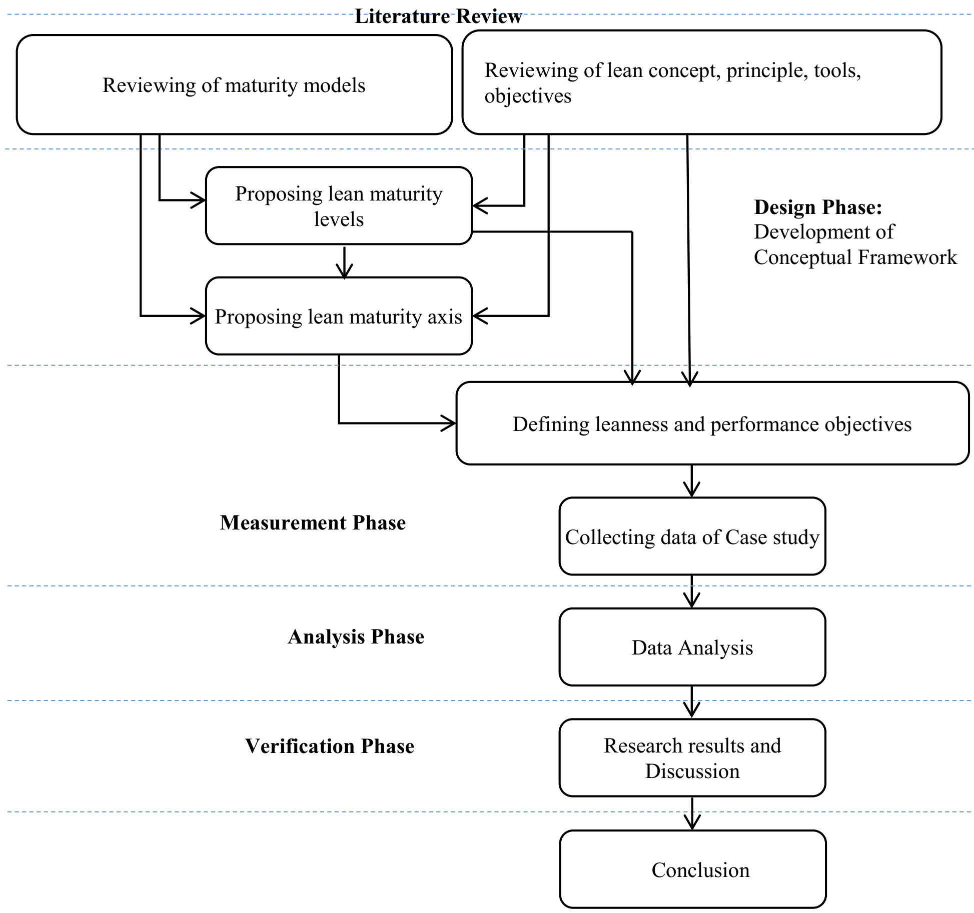
Step 1-1: maturity levels Applying the characteristics of maturity models to the scope of MCs and considering change-management principles and evolution concept of lean manufacturing, operational level maturity levels are developed. The results along with expected level of implementation, main focus of each level, expected level of result, and a brief description of each level are summarized in Table 1.

Nightingale [34] suggested giving the priority to effectiveness over efficiency as a principle of enterprise thinking during organizational transformation. Obviously, the organization should first focus on selecting the correct way and performing the right activities before improving the set of inputs to achieve best set of outputs during the lean implementation.

Step 1-2: maturity axes Balanced development of lean concept in all axes of lean is very important. Consequently, it is necessary to evaluate the progression of lean program in each axis. Vinodh and Chintha [24] maintained leanness as a measure of utilizing fewer inputs to achieve better outputs. Lemieux et al. [27] also defined lean as "doing more with less" by elimination of wastes and optimization of organizational resource. Using the simple concept of 5Ms from lean lexicon, manufacturing resources can be classified into man, machine, material, method and milieu (environment). In agreement with this assumption, our desired output, which is right product/service at the right time and in the right quantity, is result of a process in which the 5Ms are arranged and managed for the best possible outcomes. Looking at the lean concept from resource perspective, we can customize and define the axes of the LMM to the scope of manufacturing cells. As a result, seven axes have been suggested according to Table 2.

Step 1-3: leanness and performance indicators In third step, performance indicators are selected based on the organization's strategy. The KPIs may be different from organization to organization and even from MC to MC in each organization. Accordingly, associated leanness objectives could be different. Defining and measuring of leanness indicators and performance measures will not happen unless the model adapted to a real case. Thus, a case study is needed to adjust the general proposed framework to a customized lean assessment model. A case study is conducted for assessing the leanness of two MCs in different production lines of an automotive company where lean has been practiced for more than 7 years.

Fig. 1 Framework of the research approach



3.2 Measurement phase

In order to define and collect the data required for assessment of leanness and measurement of performance, the following steps have been pursued.

Step 2-1: definition of leanness indicators Based on the specifications of each axis and characteristics of each level, leanness indicators in each axis-level of LMM are defined. The leanness indicators measure how likely the company follows the defined path of lean implementation and how correctly they apply lean tools and techniques as they are standardized in company's production system (RPS in this case study). Leanness indicators are defined for each axis of LMM in the form of guidelines. For each leanness indicator, main control items are added in the guideline which helps better understanding of the indicators and indicates the items which should be investigated during the audit. Table 3, for example, shows the guideline of the axis facilities which is developed for the ABC Company.

Step 2-2: development of checklists for measurement of leanness indicators In the second step of measurement, different checklists are developed as data collection instruments. Each checklist consists of questions which addressed the requirements of each lean indicator. In order to quantify the result of audits, for each question, a 4-grade scoring system is used. Score 0 is assigned to the items without any evidence of application (absence of implementation). More than three major non-conformances also consider as zero. Score 1 is assigned to major non-conformances such as wrong application of a part of system. Score 3 was used for minor non-conformances which represents single observed lapse in some parts of system. More than five minor non-compliances also consider as major. Finally, score five was given to a complete accomplishment of an item's requirements. Table 4 shows a sample checklist used to gather the information related to the first indicator of axis "Production Processes" in level of "Understanding". The corresponding indicator is progress of standardizing production tasks in a MC.

Step 2-3: definition of performance indicators To evaluate the effectiveness of lean implementation in achievement of organizational objectives, performance measures are defined for each axis of LMM in two MCs of the case study. Considering the company's priorities and availability of data, a team consists of author, lean project leader, lean senior instructors, workshop manager, and supervisors selected the performance objectives through a discussion session. Target

Table 1 Four levels of lean maturity model in production cells

Focus of the level	Expected level of perception/ implementation	Expected level of results	Description
Capability of people, machine and processes	Understanding (training, standardization)	Quantitative progression of standardization	Quantitative progress in deploying the tools/concepts to raise awareness of the issue
		Qualitative Progression of standardization	Qualitative progress in deploying the tools/concepts in order to deepen understanding of the issue
Results and Performance	Implementation	Effectiveness	Deployment of tools/concepts in a way that is conducive to the achievement of expected results.
	Improvement	Efficiency	Deployment tools/concepts in a way that achieving the expected results and simultaneously uses resources efficiently.
Autonomy and flexibility	Sustainability	Daily Excellence	Deployment tools/concepts and improve results continuously and autonomously

value and worst case value of each performance indicator is also determined based on the historical and benchmarking data as desired and minimum expected value of each indicator.

3.3 Analysis phase

The groups of structured data obtained from case study are analyzed descriptively in the following steps:

Step 3-1: calculation of overall leanness Based on the results of audit which are summarized in the checklists, leanness of each lean indicator is calculated in the scale of 0 to 1. The overall leanness of each axis is calculated based on sum of leanness scores up to the first uncompleted level of each axis. Finally, overall leanness of each MCs is suggested as minimum of overall leanness between seven axes of LMM.

Step 3-2: calculation of overall performance in each axis of LMM Different sets of indicators with different scales are proposed to measure the performance of each MCs. Performance measurement is a multidimensional concept [28]. Therefore, a method is needed to synthesize their various dimensions with different scales into a unified index. Referring back to the review of literature on lean assessment models, a fuzzy synthetic

Table 2 LMM axis

People	- Empowerment - Improvement - Motivation - Team work
Facilities Management	- Standardization of daily maintenance activities - Autonomous maintenance - OEE calculation and improvement - Preventive, predictive and proactive maintenance - Elimination of equipment's waste and anomalies
Working Condition	- Safety and Ergonomics - Environmental Conditions
Production Processes	- Standardization of production processes - Process capability analysis and improvement
Quality	- Quality control - Reactivity - Preventive quality control (FMEA, SPC, Poka Yoke)
JIT	- Inventory control and inventory level reduction - Heijunka
Leadership	- Goal setting and action planning - Review meetings - etc

Table 3 Leanness indicators of axis facilities

Level	Indicators	Main control items
1.Understanding	A. **Stability** of machines through **standardizing maintenance tasks** in manufacturing cell	- Percentage of standardized maintenance tasks by supervisor (target 100%) - Standards are available and updated - Quality of prepared standards (e.g. clarity, using visual descriptions, validation , time associated) – control by checklist
	B. **Stability** of machines through progression of **training** on maintenance tasks in manufacturing cell and Capability of employees in analysis of loses - Progression of training on types of losses in manufacturing cel	- 100% training on corrective execution of maintenance tasks - Operators knowledge on maintenance tasks, key safety points, key maintenance points, control limits, etc - Operators knowledge on defined types of losses
	C. Improve **flow** - Progression of standardizing **set-up/shutdown** processes in manufacturing cell	- Percentage of standardized set-up/shut down tasks by supervisor (target 100%) - Standards are available and updated - Quality of prepared standards (e.g. clarity, using visual descriptions, validation , time associated) – control by checklist
	D. Improve flow - Progression of training on **set-up/shutdown** processes in manufacturing cell	- 100% training on corrective execution of set-up/shut down tasks - Operators knowledge on set-up/shut down tasks, key set-up/shut down points, etc
2.Implementation	A. Create **stability** in machines - Corrective execution of maintenance task in manufacturing cell according to standards	- Percentage of compliance (e.g. sequence, time, safety points) using checklist
	B. Create stability in machines - Accomplishment of maintenance task in manufacturing cell according to schedule	- Percentage of compliance with schedule
	C. **Capability** of employees in analysis of loses - Percentages of anomalies detected by supervisors/ operators in manufacturing cell	- Number of anomalies detected by supervisor or operator / total number of anomalies detected
	D. Improve flow - Percentages of **set-up/shut down** processes done by operators in manufacturing cell according to standards	- Number of set-up/shut down processes done by operator / total number of set-up/shut down processes
3.Improvement	A. Improve **stability** in machines through improvement of **maintenance task standards**	- Percentage of reduction in time of maintenance task
	B. Percentage of **Preventive maintenance** task to corrective maintenance tasks	- Preventive maintenance hours / corrective maintenance hours
	C. Improvement of **set up/shut down** task standards (improve **flow**)	- Percentage of reduction in set up/shut down time
	D. Decrease Cost of maintenance through improvement of internal **schedule maintenance** based on the past data history	- Total time of maintenance task
4.Sustainability	A. Calculation and improvement of **maintenance cost** by team members according to analysis of KPIs in manufacturing cell (encourage collaboration and autonomy)	- Maintenance work hours - Cost of missing production due to down time - Cost of inspection - Cost of parts/material
	B. Percentage of losses eliminated by team members within manufacturing cell through **analysis** and problem solving processes (encourage collaboration and autonomy)	- Percentage of losses eliminated by team members / total number of losses
	C. Calculation and improvement **set up/shutdown cost** by team members according to analysis of KPIs in manufacturing cell (encourage collaboration and autonomy)	- Set up/shutdown cost in manufacturing cell
	D. Sustainable improvement of stability in machines - Steady trend of improvement on facilities' **stability** and performance indicators such as downtime and OEE through internal and external (if applicable) **benchmarking** of maintenance best practices	- Facilities management indicators

Table 4 Sample of questions used for measurement of leanness indicators

Control Item: Standard Operating procedure (SOP) Axis: 4 - Production Processes Level: 1- Understanding Control Item Code: L_{141}						
Questions	**Score**					**Evidence**
	0	**1**	**3**	**5**	**N/A**	
Are the standards up to date?						
Are the standards available in production cells?						
Are the key points written precisely?						
Are the reasons of key points written clearly?						
Are the works broken down into reasonable steps?						
Are the main steps detailed enough? e.g. way of picking up and grasp						
Are all fields of standard completed correctly?						
Are the sequences of operations clearly defined?						
Are the time of each main steps and total time calculated precisely?						
Are visual descriptions used in documentation of work description?						
Are the engineering specifications written in accordance with engineering requirement?						

index as a composite indicator [29] can be used to calculate overall performance of each lean dimension.

Fuzzy logic is a form of many-valued logic in which everything is a matter of degree [30]. Behrouzi and Wong [18] suggested using fuzzy membership functions to quantify lean performance. This method is also applicable and useful for measurement of MC's performance related to lean initiatives. The following basic definitions of fuzzy logic are used to calculate the overall performance of MCs:

Definition 1 [31] A fuzzy set $\tilde{A}$ in a universe of discourse X is characterized by a membership function $\mu_{\tilde{A}}(x)$ which associates with each element x in X a real number in the interval [0, 1]. The function value $\mu_{\tilde{A}}(x)$ is termed the grade of membership of x in $\tilde{A}$.

$$\tilde{A}\left\{\left(x, \mu_{\tilde{A}}(x)\right) \middle| x \in X, \mu_{\tilde{A}}(x) \in [0, 1]\right\}$$

Definition 2 [32] Membership function in a trapezoidal-shape fuzzy set is defined as $\mu_{\tilde{A}}$ $(x; a,b,c,d)$,

$$\mu_{\tilde{A}}(x; a, b, c, d) : \begin{cases} 0 & if \quad x \leq a \quad \text{or} \quad x > d \\ \frac{x-a}{b-a} & if \quad a < x \leq b \\ 1 & if \quad b < x \leq c \\ \frac{d-x}{d-c} & if \quad c < x \leq d \end{cases}$$

Definition 3 [32] In an R-shape trapezoidal fuzzy set, $a=-\infty$, and in an L-shape trapezoidal fuzzy set, $d=+\infty$

Different performances measures are used in each axis of LMM. Each represents one aspect of MC. Fuzzy membership values are used to condense them into a scale of 0 to 1, and conjunctive composite indicators [29] are used to aggregate multidimensional performance indicators into one. In a comprehensive lean system, all of each level's objectives should be met simultaneously. Therefore, minimum of fuzzy membership values among all performance measures of each axis gives the overall performance of MCs in that axis. This allows to focus on the gaps in each level of maturity and to fulfill the requirements of each level before going further to the higher levels. It makes foundation of the system stable enough for sustainable improvements when organization becomes more mature.

Step 3-3: analysis of lean effectiveness Finally, the overall leanness indicator in each axis of LMM is compared to the result of overall performance of that axis in order to evaluate effectiveness of lean practices on achievement of MC's objectives.

3.4 Verification phase

Considering both validity of results and time factor, the theoretical validity of model initially is examined by comparing its elements with general design principles of maturity models [33]. The theoretical development phase is completed at the academic level by collecting the information through a comprehensive review of the existing literature. Long with the verification of model requirements in theory, the model is also validated practically in an industry scenario. Two MCs of the case study are selected based on the different times they had started to implement lean. Considering the factor of time, being in different stages of lean implementation provides variant sources of data for validation and generalizability of the model in two samples.

4 Data collection and analysis

To facilitate the process of data collection and analysis, a unique code is assigned for each leanness indicator and performance measure. Table 5 shows the main parameters used in the calculation of leanness and lean effectiveness. The following notations describe each parameter.

Table 5 Coding of leanness indicators and performance measures

Performance P_{JK}	$P_{11}, P_{12}, \ldots, P_{1k}$ $k = 1,2, \ldots, n_1$	$P_{21}, P_{22}, \ldots, P_{2k}$ $k = 1,2, \ldots, n_2$	$P_{31}, P_{32}, \ldots, P_{3k}$ $k = 1,2, \ldots, n_3$	$P_{41}, P_{42}, \ldots, P_{4k}$ $k = 1,2, \ldots, n_4$	$P_{51}, P_{52}, \ldots, P_{5k}$ $k = 1,2, \ldots, n_5$	$P_{61}, P_{62}, \ldots, P_{6k}$ $k = 1,2, \ldots, n_6$	$P_{71}, P_{72}, \ldots, P_{7k}$ $k = 1,2, \ldots, n_7$
Sustainability $i = 4$							
Improvement $i = 3$					L_{351}, L_{352}, …, L_{35m}		
Implementation $i = 2$							
Understanding $i = 1$		L_{211}, L_{212}, …, L_{21m}					
Lean maturity levels (i) / Lean maturity axes (*j*)	People $j = 1$	Facilities $j = 2$	Working conditions $j = 3$	Production processes $j = 4$	Quality $j = 5$	JIT $j = 6$	Leadership $j = 7$

L_{ijm} example: m=1,2, …, n_{ij}

Notations

i	Level of maturity i=1,2,3 or 4
j	Axis of LMM j=1,...,7
L_{ijm}	m^{th} leanness indicator of level i axis j
L_{ij}	Leanness of level i axis j
LA_j	Overall leanness of axis j
LL_j	Overall leanness of level i
L	Overall leanness of a production cell
P_j	Overall performance of axis j
P_{jk}	k^{th} performance indicator of axis j
n_j	Number of performance indicators in axis j
n_{ij}	Number of leanness indicators in level i axis j
a_{Pjk}	Target value of performance indicator P_{jk}
b_{Pjk}	Worst case value of performance indicator P_{jk}
r_{Pjk}	Real value of performance indicator P_{jk}

In order to help normalize the result of observations, according to equation (1), all leanness indicators are converted to the scale of 0 to 100. A unique code in the format of L_{ijm} is formed by using the indices as shown above. For example, i=3, j=5, and m=1 forms the code L351 which correspond to the first indicator of axis 5 (axis quality) in level 3. According to the formula, weights 0, 3, and 5 have been assigned to a_1, a_2, and a_3 which are the total number of major non-conformances, minor non-conformances, and conformances, respectively, according to the audit checklist questions. The numerator in the fraction is the weighted sum of audit scores, and the denominator shows the maximum achievable audit score based on the number of applicable questions. Results of leanness indicators obtained through audits and direct observation of MC1 are summarized in Table 6.

$$L_{ijm} = \frac{a_1 + 3a_2 + 5a_3}{5 \times \text{number of applicable questions in the checklist}} \times 100 \tag{1}$$

4.1 Overall leanness

The ultimate objective is to calculate the overall leanness of each MC, but first, we start calculating the leanness of each axis at each level. There is more than one way of doing this calculation. One can calculate the average of leanness indicators as well as the standard deviation and interpret the results accordingly. Alternatively, one can use the minimum value of the indicators hence using the weakest indicator to characterize the leanness of an axis at a certain level. One major drawback of the former approach is that two indicators with values of 25 and 75 % will result in an average of 50 % leanness for that axis at a certain level. In this study, we adopt a more conservative approach in characterizing leanness, and hence, we chose the latter approach, which would give 25 % leanness to the abovementioned example and hence highlights the need for major improvements in the indicator(s) responsible for this result.

The leanness indicators in each axis j at level i (L_{ij}) are calculated by using equation (2) which chooses the

Table 6 Leanness indicators—production cell 1

	People		Facilities		Working Condition		Production Processes		Quality		JIT		Leadership	
	Indicator code	MC1-ASSEMBLY	Indicator code	MC1-ASSEMBLY	Indicator code	MC1-ASSEMBLY	Indicator code	MC1-ASSEMBLY	Indicator code	MC1-ASSEMBLY	Indicator code	MC1-ASSEMBLY	Indicator code	MC1-ASSEMBLY
Level 1	L111	100	L121	100	L131	100	L141	100	L151	100	L161	100	L171	85
	L112	100	L122	100	L132	100	L142	100	L152	100	L162	100	L172	100
	L113	100	L123	87	L133	100	L143	100	L153	100	L163	100	L173	100
	L114	100	L124	70	L134	100			L154	100	L164	100	L174	100
	L115	100			L135	100			L155	100	L165	100		
					L136	N/A			L156	100				
					L137	N/A			L157	100				
									L158	100				
									L159	100				
									L1510	100				
									L1511	100				
	Min	100	Min	70	Min	100	Min	100	Min	100	Min	100	Min	85
Level 2	L211	100	L221	69	L231	90	L241	87	L251	82	L261	86	L271	80
	L212	70	L222	100	L232	84	L242	100	L252	85	L262	100	L272	100
	L213	65	L223	72	L233	100			L253	100	L263	87	L273	84
	L215	100	L224	100	L234	60			L254	79	L264	100	L274	73
	L216	100			L235	N/A			L255	90	L265	76		
									L256	100	L266	90		
	Min	65	Min	69	Min	60	Min	87	Min	79	Min	76	Min	73
Level 3	L311	80	L321	58	L331	80	L341	69	L351	60	L361	45	L371	0
	L312	100	L322	35	L332	24	L342	40	L352	0	L362	32	L372	0
	L313	80	L323	0	L333	63			L353	60	L363	100	L373	0
	L314	15	L324	0	L334	23			L355	0	L364	0		
	L316	0			L335	N/A			L356	0	L366	100		
					L336	N/A					L367	15		
											L368	54		
	Min	0.0	Min	0.0	Min	23.0	Min	40.0	Min	0.0	Min	0.0	Min	0.0
Level 4	L411	0	L421	0	L431	0	L441	0	L451	0	L461	0.0	L471	0
	L412	0	L422	0	L432	0	L442	0	L452	0	L462	0.0	L472	0
	L413	0	L423	0	L433	0	L443	0	L453	0	L463	0.0	L473	0
	L414	0	L424	0	L434	0			L454	0	L464	0.0		
	L415	0			L435	0								
	Min	0	Min	0	Min	0	Min	0	Min	0	Min	0	Min	0

Table 7 Leanness indicators of each axis

Axes	1	2	3	4	5	6	7
	MC1 - L_{ij}						
Level 1	1	0.7	1	1	1	1	0.85
Level 2	0.65	0.69	0.60	0.87	0.79	0.76	0.73
Level 3	0	0	0.23	0.40	0	0	0
Level 4	0	0	0	0	0	0	0
Axes	1	2	3	4	5	6	7
	MC2 - L_{ij}						
Level 1	0.8	1	0.6	1	0.55	1	0.6
Level 2	0.53	1	0	0.75	0.43	0.55	0
Level 3	0	0.57	0	0	0	0	0
Level 4	0	0	0	0	0	0	0

minimum value. Leanness indicators are also divided by 100 to scale them to 0 to 1 which is the major gridline of maturity levels. Table 7 shows the results of these calculations. If a leanness indicator was not applicable to a manufacturing cell, the N/A is shown in related row in Table 6 and that indicator is not considered in the calculation of overall leanness.

$$L_{ij} = \min\{L_{ij}/100; m = 1, .., n_{ij}\} \qquad (2)$$

To analyze leanness of MCs, first, the results of calculations are transferred to the visual form of LMM as depicted in the Fig. 2. Visual presentation of leanness in each level gives us an insight into how lean initiatives resulted in understanding, implementation, improvement, and sustainability of lean principles.

As can be seen from the Fig. 2, in MC 1, good progress was made to achieve the leanness objectives in level 1 and level 2. However, there are still some progress to be made in the axes facilities and leadership, in which the leanness index at level 1 is 0.70 and 0.85, respectively. By referring back to the Table 6, we can identify the source of non-conformances. As data in the table demonstrates, failure to achieve the level 1 is related to three main control items: *L123* and *L124* in the axis of facilities and *L171* in the axis of leadership. By further analysis of these indicators and revision of audit results, appropriate actions can be identified and implemented to fill up the gaps.

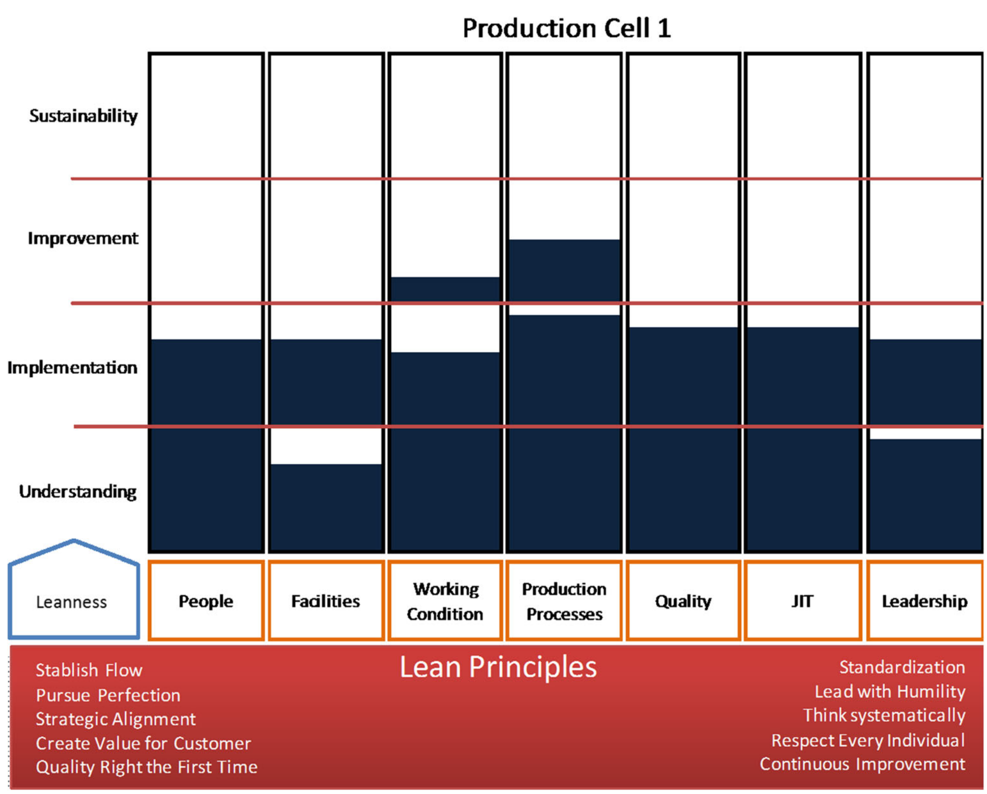


Fig. 2 leanness results—production cell 1

Overall leanness of each maturity level (LL_i) Considering balanced progress of lean as a basic principle of implementation, the minimum score between all axes of LMM is chosen to assess the overall leanness of each level. Thus, according to equation (3), LL_is are considered as overall indicators of MC's leanness in each level. This approach encourages the associated team of MC to focus on the dimensions with less progress in a certain level and resolve the existing shortcomings before going forward in other dimensions where more progress is made. In the case of MC1, if the small current non-conformances in the axes facilities and leadership are eliminated, overall leanness will change from 0.89 (which is the minimum of the leanness indicators in level 1) to 1 which shows the completion of level 1.

For each level i,

$$LL_i = \min\{L_{ij}; j = 1, \dots, 7\} \quad i = 1, 2, 3, 4 \tag{3}$$

Overall leanness of each maturity axis (LA_j) One of the important roles of lean assessment is to highlight the gaps in each level of maturity. Consequently, action plans can be defined and prioritized in order to fill the gaps and create a synchronized and balanced continuous progress. In order to focus on the mentioned gaps, completion of each level's activities is considered in calculation of overall leanness of each axis. For instance, in MC1, the leanness of level 1 and 2 in the axis quality is 1 and 0.79 respectively. Thus, the overall leanness of axis quality is equal to 1.79 (1+ 0.79). Although some progress has been made at third level in the indicators of *L351* and *L353*, considering minimum as the overall leanness, they have not been accounted for in calculations.

Equation (3) is used to calculate the overall leanness of each axis based on the suggested rule.

For each axis,

$$\begin{array}{llll} \text{if} & L_{1j} < 1 & \rightarrow LA_J = L_{1j} & \text{otherwise} \\ \text{if} & L_{2j} < 1 & \rightarrow LA_J = 1 + L_{2j} & \text{otherwise} \quad j = 1, \dots, 7 \\ \text{if} & L_{3j} < 1 & \rightarrow LA_J = 2 + L_{3j} & \text{otherwise} \\ & & LA_J = 3 + L_{4j} & \end{array} \tag{4}$$

It should be noted that leanness of maturity axis LA_j is on a scale of 0 to 4, meaning that in an axis where current lean journey is completed, the value is 4. The results of calculations are summarized in Table 8. As the results show, in the axes 1, 3, 4, 5, 6, MC1 has completely accomplished the requirements of level 1 and also met the requirements of level 2 to a certain extent, whereas more effort is necessary in axes 2 and 7 which have not yet reached level 1.

Overall leanness of production cell (L) In order to emphasize on the balanced progress of lean in all axis of LMM and focus the efforts on the axes with less progression, minimum of leanness between all axes (minimum of LA_js is suggested as the indication of overall leanness in a MC. Referring back to the results of leanness indicators in each axis of LMM in the last row of Table 6, according to the equation (4), overall leanness of MC1 is 0.70. However, it should also be noted that overall leanness measure L is on a scale of 0 to 4, as it requires the completion of all four levels.

$$L = \min\{LA_j; j = 1, \dots, 7\} \tag{5}$$

4.2 Overall performance

A list of performance measures are used to measure the performance of each axis. Table 9 depicts the performance

Table 8 Leanness indicators of each axis

Axes	1	2	3	4	5	6	7
	L_{ij}						
Level 1	1	0.70	1.00	1.00	1.00	1.00	0.85
Level 2	0.65	0.69	0.6	0.87	0.79	0.76	0.73
Level 3	0	0	0.23	0.40	0	0	0
Level 4	0	0	0	0	0	0	0
LA_j	1.65	0.70	1.6	1.87	1.79	1.76	0.85

Table 9 Performance measures

Axis (j)	Performance Measure (k)	performance code (P_{jk})	Equation	Desired trend	Target value	Worst case value
People	Absenteeism Rate	P11	Total number of man days lost due to absenteeism in last 12 months / Total number of working man days available in last 12 months	↓	0.03	0.07
	Multifunctionality of Operators	P12	Total number of operators with skill level 3 in more than 3 workstations in production cell, skill level 3 in 1 workstation in supplier's production cell and 1 workstation in customer's production cell / total number of operators	↑	1	0
Facilities	Uptime	P21	(Total number of working hours in last 12 months – total downtime hours with the cause inside production cell in last 12 months)/ Total number of working hours in last 12 months – planned maintenance in last 12 months	↑	0.97	0.85
	MTBF	P22	Total up time in last 12 months / Total number of breakdowns in last 12 months	↑	170	100
	MTTR	P23	Total downtime hours for maintenance in last 12 months / Total number of breakdowns in last 12 months	↓	0.5	2
Working Conditions	Safety Risk Factor	P31	3* Number of high risk WS + Number of medium risk WS / Total number of WS	↓	0	0.3
	Ergonomics Risk	P32	3* Number of high risk WS + Number of medium risk WS / Total number of WS	↓	0	0.6
Production Processes	Value-added Rate	P41	Value-added time / Total processing time	↑	0.9	0.65
	Balance Efficiency	P42	Processing time / Number of operators * cycle time	↑	0.9	0.7
Quality	Scrap Rate	P51	Total number of parts scraped in last 12 months / Total number of parts produced or used	↓	0	0.03
	Rework	P52	Total rework hours in last 12 months / Total working hours in last 12 months	↓	0.02	0.08
	FPY	P53	units of products completed in production cell with no rework in last 12 months / total units of products entering production cell in last 12 months	↑	0.97	0.85
JIT	On-time Delivery	P61	(3*Sum absolute value of tardiness in hours + Sum absolute value of earliness) / Total deliveries in last 12 months	↓	0	1
	Inventory Turnover Ratio	P62	Cost of goods sold in last 12 months/ Average inventory in last 12 months (calculated just for parts group A in production cell)*	↑	195	160
Leadership	Average Performance	P71	Average percentages of meeting target value of each performance measure	↑	0.25	0
				↑	0.5	0.26
				↑	0.75	0.51
				↑	1	0.76

WS work station, *MTBF* mean time between failures, *MTTR* mean time to repair, *FPY* first pass yield

* Inventory turnover ratio was calculated based on the group A parts in production cell. As a result, the value is bigger than what is usually calculating for a company

indicators of seven axes of LMM along with their targets and worst case values in MC1. Performance indicator P_{jk} represents the performance indicator for axis j and measure k. For example, the performance of axis 1 (people) is measured by absenteeism and multi-functionality of operators and represented by P_{11} and P_{12}, respectively. Symbols ↑ and ↓ in the table show the desired direction in which the value of performance is expected to improve.

The results of data collection on performance indicators of case study are presented in Table 10. For example, absenteeism in people axis (P_{11}) is currently at 0.06 (6 %) in MC1 and has the next target and worst case values as 0.03 (3 %) and 0.07 (7 %), respectively. Furthermore, desired trend as demonstrated by symbol ↓ is to decrease this measure from its current value of 0.06 to its next target value of 0.03.

As demonstrated in Table 10, different performance measures with different scales are used to measure the lean performance in each dimension of LMM. Fuzzy membership values can be assigned to actual performance values to represent the degree of achievement of the corresponding performance.

For the performance measures P_{11}, P_{23}, P_{31}, P_{32}, P_{51}, P_{52}, and P_{61} in which the worst cases are the upper acceptable limit of performance measure, a trapezoidal R-function is used to calculate the corresponding membership values. As shown in equation (5), the target level is defined as C_{Pjk} and the lower threshold is defined as d_{Pjk}. For example, the defined target of P_{32} is 0 and its worst case is 0.6, which means the fuzzy membership value of actual value of P_{32} (0.4) is μ(0.4)=(0.6–0.4/0.6)=0.33. Membership value calculations related to MC1 are shown in Fig. 3 and summarized in Table 11.

$$\mu_{\tilde{A}}(r_{Pjk}) = \begin{cases} 0 & r_{Pjk} > \ d_{Pjk} \\ \dfrac{d_{Pjk}-r_{Pjk}}{b_{Pjk}-c_{Pjk}} & C_{Pjk}\cdot \le X_k \le d_{Pjk} \\ 1 & r_{Pjk} < \ C_{Pjk} \end{cases} \tag{6}$$

For the performance measures P_{12}, P_{21}, P_{22}, P_{41}, P_{42}, P_{53}, and P_{62} in which the worst cases are lower acceptable limits, trapezoidal L-function is used. The lower acceptable level is defined as a_{Pjk} and the target is defined as b_{Pjk} Equation (6) is used to calculate fuzzy membership values of the mentioned performance measures. For example, the target of P_{12} is 1 and its worst case is 0 which means the fuzzy membership value of P_{12} is equal to its real value of P_{12} which is 0.8. For the remaining performance measure, the results of calculations are plotted in Fig. 4 and summarized in Table 11.

$$\mu_{\tilde{A}}(r_{Pjk}) = \begin{cases} 0 & r_{Pjk} > \ a_{Pjk} \\ \dfrac{r_{Pjk}-a_{Pjk}}{b_{Pjk}-a_{Pjk}} & a_{Pjk}\cdot \le r_{Pjk} \le b_{Pjk} \\ 1 & r_{Pjk} < \ b_{Pjk} \end{cases} \tag{7}$$

Table 10 Data collection results on performance measures

Performance indicator (P_{jk})	Desired Trend	Production Cell 1			Production Cell 2		
		Actual Value ($r_{P_{jk}}$)	Next Target value	Worst case value	Actual Value ($r_{P_{jk}}$)	Next Target value	Worst case value
P11	↓	0.06	0.03	0.07	0.05	0.03	0.07
P12	↑	0.8	1	0	0.4	`1	0
P21	↑	0.92	0.97	0.85	0.95	0.97	0.85
P22	↑	125	170	100	162	185	100
P23	↓	1.05	0.5	2	1.5	0.8	3
P31	↓	0.22	0	0.3	0.27	0	0.3
P32	↓	0.4	0	0.6	0.5	0	0.6
P41	↑	0.8	0.9	0.65	0.75	0.9	0.65
P42	↑	0.85	0.9	0.7	0.6	0.9	0.7
P51	↓	0.012	0	0.03	0.05	0	0.03
P52	↓	0.06	0.02	0.08	0.12	0.03	0.08
P53	↑	0.92	0.97	0.85	0.88	0.97	0.85
P61	↓	0	0	1	0	0	1
P62	↑	180	195	160	192	210	175
P71	↑	0.40	0.25	0	0.33	0.25	0
			0.5	0.26		0.5	0.26
			0.75	0.51		0.75	0.51
			1	0.76		1	0.76

In a comprehensive lean system, achievement of all defined objectives up to a targeted level should be considered in each step in order to make simultaneous progress in all dimensions. Therefore, the minimum of fuzzy membership values in each axis of LMM is suggested as the measure of overall performance of that axis. In other words, according to equation (8), a conjunctive fuzzy composite index P_j is suggested to measure the overall performance of each lean dimension j.

For each axis j

$$P_j = \min\left\{ \mu_{\tilde{A}}\left(r_{Pjk}\right); k = 1, ..., n_j \right\} j = 1, ..., 7 \quad (8)$$

The results of P_j calculations for MC1 and MC2 are given in the Table 11 and plotted in Fig. 5.

5 Analysis of results

In order to analyze the results, data of leanness assessment and measured performance can be combined together in a single visual format as demonstrated in Fig. 6. Comparing the result of leanness and performance in each axis gives us an overall idea on effectiveness of lean initiatives in that axis. By a quick overview of graph in Fig. 6, it can be easily be observed that lean practices in axes facilities, production processes, JIT and leadership resulted in a good level of performance in MC1. On the other hand, in axis people, working condition and quality, performance results are lacking behind the lean effort.

To analyze the gap between leanness and performance in detail, one can refer back to the records of performance and leanness. For example, it can be seen that the low performance in the axis of "Working Condition" is related to the performance measures P_{31} and P_{32} which are the indicators of safety and ergonomics risk. Analyzing the result of leanness indicators in the same axis also shows that 40 % gap between the leanness indicators and the target of level 2 in the axis of working condition is related to the main control item *L234* (60 of 100). *L234* is the control item of basic ergonomics analysis. Comparing the results of this example shows that by corrective execution of ergonomic analysis in MC1 and accomplishment of the *L234*'s requirements, corresponding performance measure (P_{32}) can be improved. Consequently, the leanness level will move to the next minimum value which is 0.84 which belongs to *L232*. According to the equation (3), new value of overall leanness of working condition will change to the value of 1.84. *L232* is the control item of safety audit in level 2 (input). P_{31} is also the performance measure of safety risk (output). Thus, by analysis of input and implementation of appropriate action plans to fulfill the safety requirements in MC1, lower risk of safety is expected while MC1 will reach the maturity level 2 in the axis of working conditions.

While the performance is lower than the expected value in some axes such as working condition, it may still be higher than expected as considered to the level of leanness. For

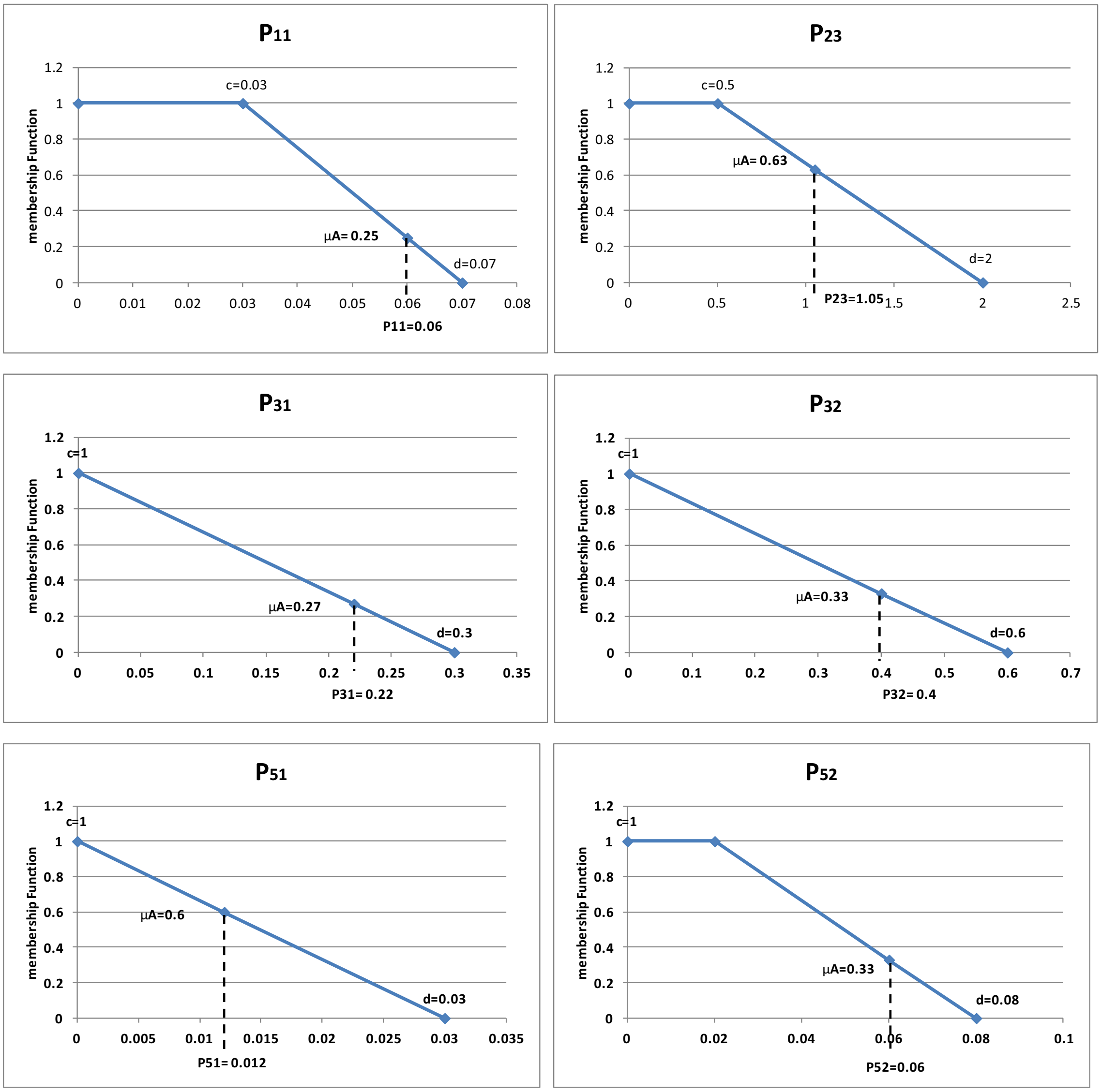


Fig. 3 Fuzzy membership function of performance measures P_{11}, P_{23}, P_{31}, P_{32}, P_{51}, and P_{52}

example, in axis of JIT in MC1, as Fig. 6 shows, the overall leanness has not yet reached the level 2; however, the overall performance is more than the half of the target. Although the results are satisfactory in terms of target achievement in this axis, more analysis is required in these cases to fill the gaps in requirements of leanness.

In addition to visual analysis of results, the effectiveness of lean initiatives in each axis of LMM can be analyzed more precisely by comparing the current performance of each dimension with its expected performance based on the current level of leanness. Conjunctive combination of performance indicators are used to calculate the overall performance measure of each axis as identified by P_j in Table 11. The result is a fuzzy membership value between 0 and 1 indicating the degree with which the targeted performance is reached.

As for the expected performance based on the current level of leanness, it is interpreted that the expected level of performance in level 0 starts from 0 and reaches value 1 in level 4. According to equation (3), leanness of axis LA_j is defined on a scale of 0 to 4 and hence needs to be mapped to a scale of 0 to 1. This mapping can be done by a simple trapezoidal L-function with a=0 b=4, and c=d=∞, as shown in equation (7).

$$\mu_{\underset{EXP}{\sim}}\left(LA_j\right) = LA_j/4 \tag{10}$$

For example, the level of leanness in the axis of production process (LA_4) in MC1 is calculated as 1.87 (see Table 8). By using equation (7), this corresponds to a membership value of 0.465 which indicates that the expected overall performance

Table 11 Overall performance of each axis based on minimum fuzzy membership function

Axis (j)	Performance indicator r_{Pjk}	Manufacturing cell 1		Manufacturing cell 2	
		$\mu_{\tilde{A}}(r_{Pjk})$	P_j	$\mu_{\tilde{A}}(r_{Pjk})$	P_j
1. People	P11	0.25	0.25	0.5	0.4
	P12	0.8		0.4	
2. Facilities	P21	0.58	0.36	0.83	0.68
	P22	0.36		0.73	
	P23	0.63		0.68	
3. Working condition	P31	0.27	0.27	0.1	0.1
	P32	0.33		0.17	
4. Production processes	P41	0.6	0.6	0.4	0.3
	P42	0.75		0.3	
5. Quality	P51	0.60	0.33	0	0
	P52	0.33		0	
	P53	0.53		0.88	
6. JIT	P61	1	0.57	1	0.49
	P62	0.57		0.49	
7. Leadership	P71	0.40	0.40	0.33	0.33

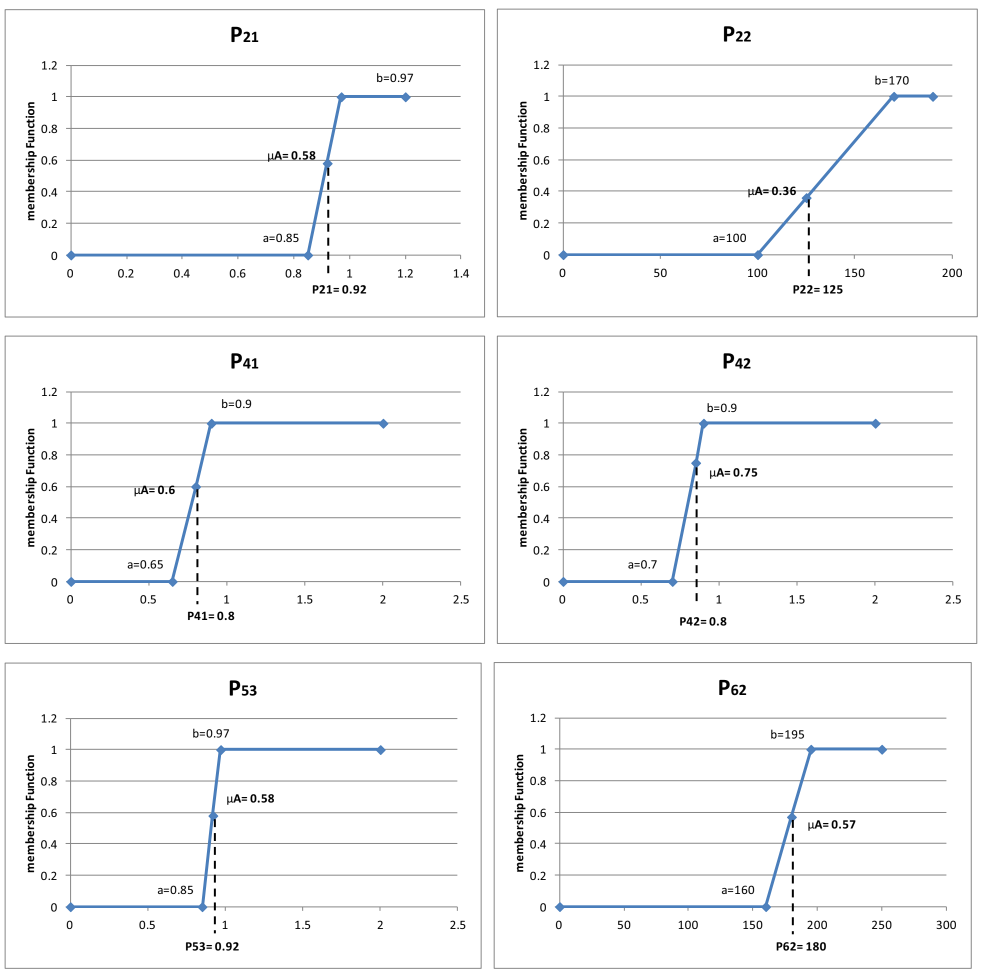


Fig. 4 Fuzzy membership function of performance measures P_{21}, P_{22}, P_{41}, P_{42}, P_{53}, and P_{62}

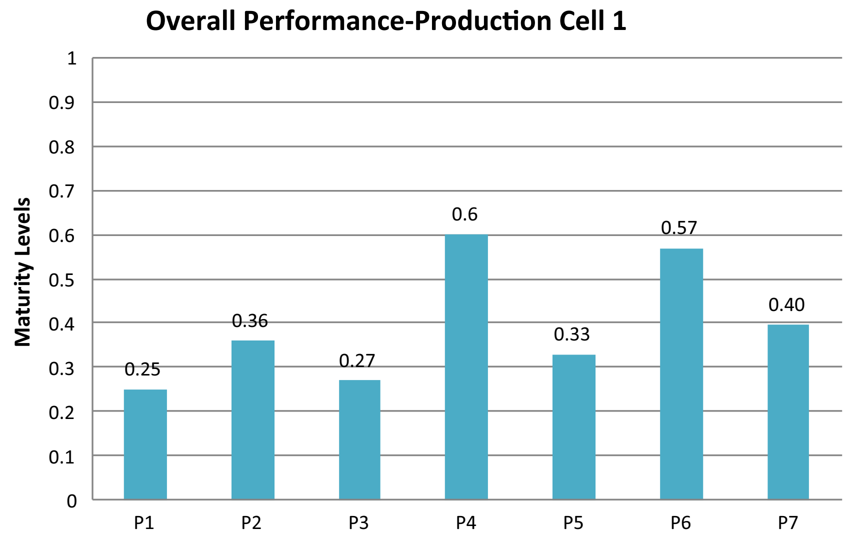


Fig. 5 Overall performance (P_j)

of axis production process in MC1 is about half of the target, which now can be compared with the actual performance.

The values of expected overall performance and actual performance are calculated and plotted in Fig. 7. For example, comparing the expected value of overall performance (0.465) with its real value (0.6) in Fig. 7 shows that the actual performance in the axis of production processes exceeded the expected value. Subsequently, the level of target achievement in percentage scale is calculated using equation (8).

$$\text{Level of Target Achievement} = \frac{P_j - \underset{\sim}{\mu}_{EXP}(LA_j)}{\underset{\sim}{\mu}_{EXP}(LA_j)} \times 100 \tag{11}$$

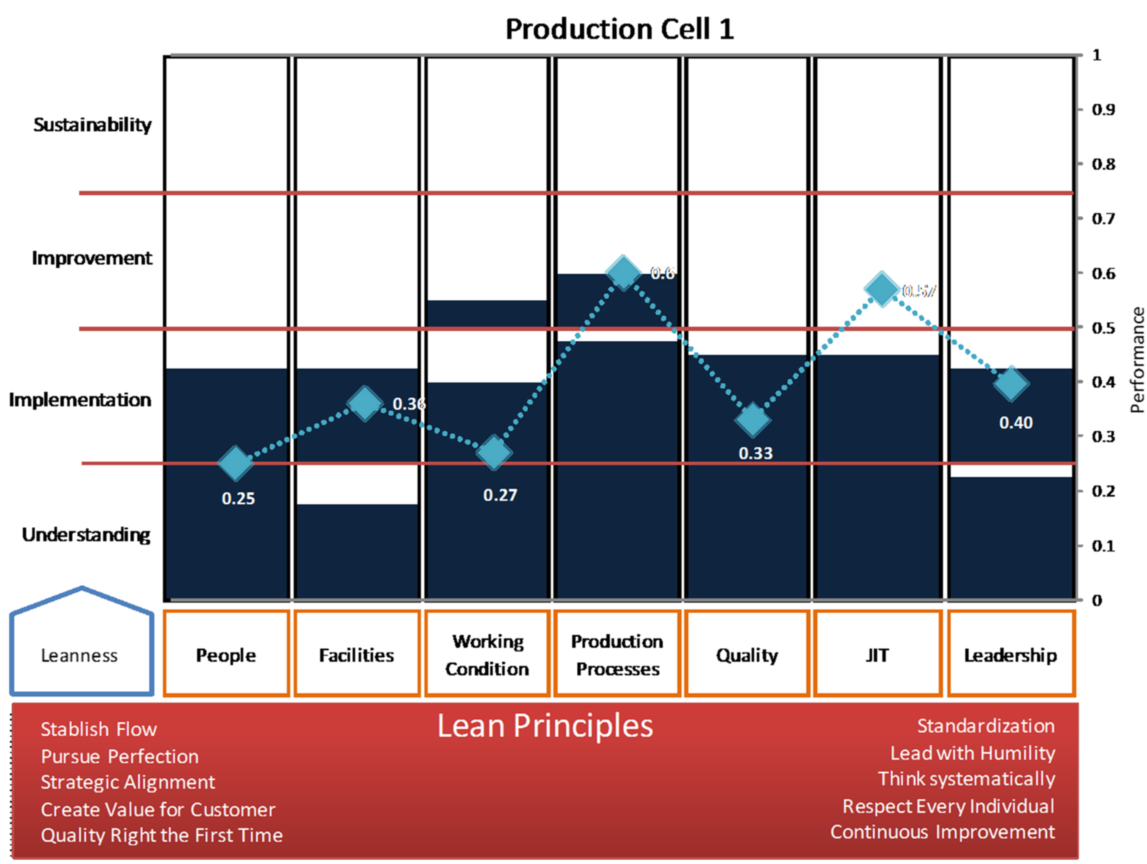


Fig. 6 Leanness and performance assessment—production cell 1

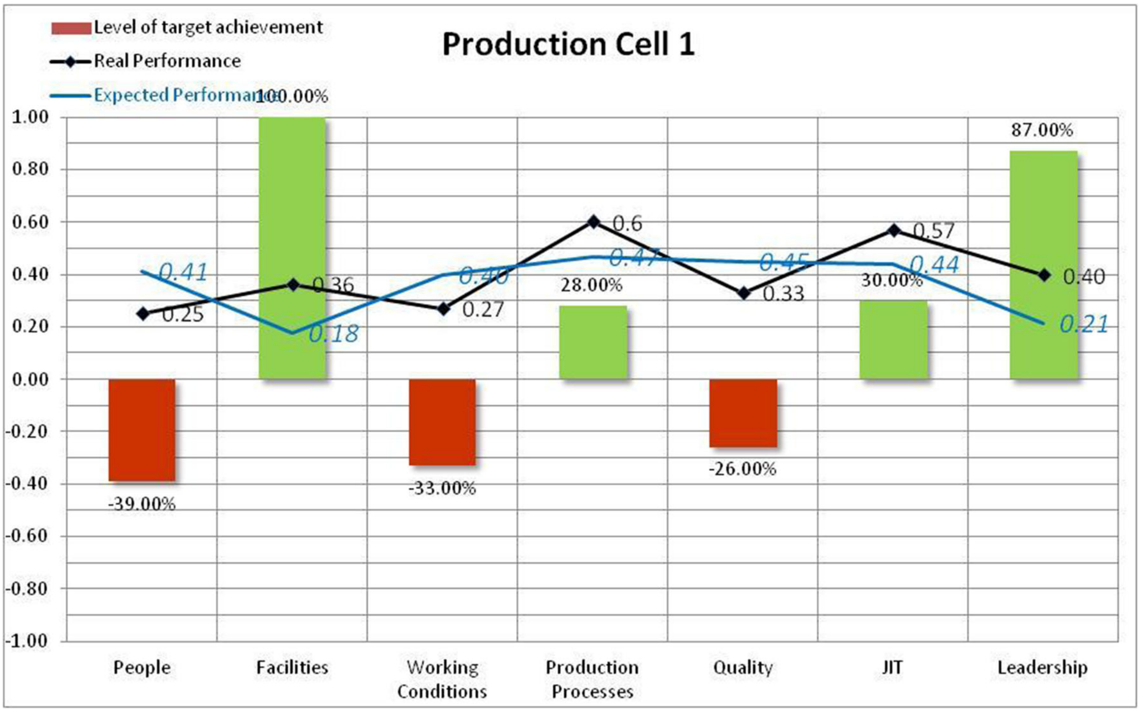


Fig. 7 Level of target achievement—production cell 1

Figure 7 compares the expected level of overall performance with its current level in each dimension of lean in MC1. The bar chart in the graph shows the level of target achievement—in the form of overachievement (+) or underachievement (−).Wherever performance objectives are not met in an axis of LMM, the bar in the negative part of vertical axis indicates the percentage that objective is behind the target—underachievement. If the current value of a performance is bigger than expected, a bar in the positive part of vertical axis shows the percentage that objective is exceeded—overachievement.

Referring back to the research questions, analysis of the data provided in Fig. 7 helps organization to evaluate and improve the effectiveness of lean practices in achievement of each MCs' performance measures. Differentiating between the axes where the targets have been achieved with those where lean has not resulted in the desired objectives helps the MC team to focus on the major gaps. In this regard, defining and implementing of the action plans to resolve the problems in the axes with the higher value of underachievement will result in improvement of overall leanness in shorter period of time. As the diagrams depicted, the axes people, working condition, and quality should be addressed accordingly in MC1.

Despite the fact that the overall leanness (*LAj*) of axis people is 1.65, it has the highest value of underachievement in MC1 (−39 %). Two indicators have been used to measure the leanness of axis people, P_{11} and P_{12} which represent the absenteeism rate and multi-functionality of operators, respectively. According to equation (8), P_{11} has been selected as overall performance (Pj) of this axis in MC1. The expected performance value based on the overall leanness is 0.41 while the corresponding fuzzy membership value of absenteeism rate is equal to 0.25. The gap between the actual and expected performance shows that the lean initiatives were not successful in improving the absenteeism rate. Referring back to the list of leanness indicators, two leanness indicators are directly linked to the absenteeism rate: *L114* which corresponds to progress of standardizing the production cell's rules (and absenteeism rule as one of them) and *L115* which corresponds to progress of training on manufacturing cell's rules. Other leanness indicators such as satisfaction (*L218*) may also affect absenteeism rate. Consequently, a problem solving approach is recommended for analysis of all possible causes and focusing on those with higher impact on the final results.

6 Conclusions

The proposed visual maturity model and suggested methodology to assess leanness of manufacturing cells is a framework to develop lean gradually and continuously at shop floor level. The model can be used by lean practitioners and can be improved in details based on the developed knowledge.

This study represents a general model of lean maturity for the manufacturing cells. Considering unique circumstances of every organization, it is recommended that each organization customizes the model based on their special situation. Consequently, assessment checklists, lean indicators, main control items, performance measures, and performance targets can be developed based on company's requirements and strategies. Furthermore, lean maturity model presented in this study focuses on the necessary activities needed in the level of operations. As an important prerequisite of the proposed model, organization must provide an overall enterprise lean transformation plan (one such LESAT-LAI). Although leanness assessment checklists are developed through development of lean program, a dynamic assessment system is suggested in which the evaluation system and its related checklists can be continuously improved by using the feedbacks of the previous assessments and by analyzing of leanness results in comparison with performance of production cells.

This research can be enhanced through testing of leanness control items in a longer term empirical study. A dynamic assessment methodology is proposed in which the assessment elements will be improved continuously through analysis of leanness results and performance of manufacturing cell. Moreover, lean maturity model can be applied on other circumstance such as service sector. Customization of model and definition of leanness elements related to each industry can be a subject of further research.

Acknowledgment This research is partially supported by Natural Sciences and Engineering Research Council of Canada (NSERC).

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