A lean manufacturing road map using fuzzy-DEMATEL with case-based analysis

Sameh N. Seleem, El-Awady Attia, Ahmed Karam and Ahmed El-Assal
Department of Mechanical Engineering, Benha University, Benha, Egypt

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Abstract

Purpose – This paper aims to develop a lean manufacturing road map for industrial firms by selecting the appropriate lean tools relying on the predefined strategic objectives and the firm constraints. It also illustrates how to prioritize these tools considering their interrelationship.

Design/methodology/approach – Relying on the predefined strategic objectives, operational objectives can be set by using the balanced scorecard (BSC). Afterwards, the theory of constraints (TOC) is introduced to investigate the manufacturing system and to determine its constraints. For these constraints, the principle of fault tree analysis (FTA) is used to determine their root causes. Consequently, lean manufacturing tools/initiatives can be proposed. Finally, the fuzzy-decision making trial and evaluation laboratory (fuzzy-DEMATEL) method is implemented to prioritize these initiatives and to construct a suitable lean road map by managing experts' knowledge.

Findings – The practical results indicate that diagnosing the manufacturing system and managing experts' knowledge to select the appropriate lean initiatives, and prioritizing these initiatives relying on the understanding of their interrelationship could support achieving the strategic targets without consuming extra time or resources.

Research limitations/implications – The study is limited to manufacturing firms. Besides, it reinforces the need for investigating the effectiveness of the proposed approach on service sectors.

Practical implications – The study provides a methodology with a real application, to manage experts' knowledge for developing an effective lean improvement road map. The methodology could be adopted by any manufacturing firm.

Originality/value – The study supports decision makers of a firm to select the improvement initiatives by an original structural approach, which integrates BSC, TOC, FTA and fuzzy-DEMATEL. Besides, the interrelationships among the selected lean initiatives are considered, and results show the importance of analysing these interrelationships during the construction of the lean improvement plan. Moreover, its effectiveness and applicability are validated via a practical case study.

Keywords Fault tree analysis, Theory of constraints, Balanced scorecard, Lean manufacturing, Fuzzy-DEMATEL

Paper type Research paper

1. Introduction

With increasing global competition, manufacturing firms are experiencing increasing pressure for improving their performance. Therefore, performance improvement plans become necessary for the success of any firm working in such a competitive environment. The effectiveness of performance improvement plans mainly depends on the methodology adopted and the experience of the firm's staff to implement such methodology (Gonzalez Aleu and Van Aken, 2016; Iyede *et al.*, 2018). Consequently, experts make an effort to develop and implement the appropriate improvement plan/road map that achieves the

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predefined strategic objectives. Yadav *et al.* (2018) reported that one of the lean barriers is the lack of an effective road map to guide the implementations. This road map should be tailored and adapted based on the understanding of both the challenges that the company faces and the manufacturing system constraints. Subsequently, it is very important to determine the main attributes of this tailored road map. On the operational level, lean manufacturing offers a set of performance improvement tools. Here, these tools are called initiatives or initiatives. It contains tools for almost all manufacturing steps. Relying on the work of Eswaramoorthi *et al.* (2011), Shetty *et al.* (2010), Sahoo and Yadav (2018) and Hakimi *et al.* (2018), lean tools for manufacturing can be listed as follows cross-functional team, work standardization, process capability, value engineering, 5S, root cause analysis, multi-skill workers, mixed model production, cycle time reduction, bottleneck elimination, employee empowerment, waste reduction, Kaizen, target costing, mistake-proofing, failure mode and effect analysis, supplier management, lot size reduction, design for manufacturing and assembly, total productive maintenance, KANBAN/pull system, visual control, single-piece flow, ergonomic work station, data analysis, quality management system, indexed flow line, line balancing, quality function deployment, total quality management, statistical quality control, layout design, cellular work station design, value stream map (VSM), autonomous maintenance, evaluation of TAKT time, motion study, single minute exchange of dies, ANDON and logistics system. For managing such massive lean tools, it is crucial to develop a conceptual structural model. Moreover, the selected tools should be adopted based on diagnosing and determining the real constraints in the manufacturing system. The weak link between lean improvement road map and real bottlenecks within the manufacturing system is considered as a critical failure factor of lean (Albliwi *et al.*, 2014).

Essentially, any manufacturing system has a set of constraints that resists the achievement of its desired operational goals. According to Cox and Blackstone (2002), any factor that prevents a system from achieving a higher level of performance can be defined as a constraint. Eliminating the effect of those constraints aligns the firm towards achieving its objectives. The exploration of constraints is a critical step for performance improvement. In this paper, the theory of constraints (TOC) is proposed for exploring system constraints by considering the three measures of Goldratt and Cox (1992), namely, throughput (the rate of generating money through sales), inventory (the cost of stocked material and products within the system) and operational expenses (all the money the system spends to turn inventory into throughput). Each firm has its own constraints, and thus it needs a tailored treatment plan. In most cases, this plan is a combination of lean improvement tools that could be used to cope with company constraints. Consequently, firms face the issue of determining which improvement tools that would achieve their strategic objectives. This real issue has not been adequately addressed in the literature of operations management (Voss, 2005; Slack *et al.*, 2006).

Identifying the constraints' root causes is vital. Root cause analysis such as fault tree analysis (FTA) can be used for such purpose. FTA can be used to analyse the system in the context of its operations to find all possible combinations of basic factors that may lead to the occurrence of a predefined event (Vesely *et al.*, 1981). By using the logic gates (OR-gate and AND-gate), this method produces a structural set of causal interrelationships and uses the experience of the problem stakeholders to determine the operational objectives and the corresponding attributes.

Based on the identified root causes, the appropriate mix of lean manufacturing tools can be introduced. However, system diagnosis, exploration of constraints and their root causes and the proposition of lean improvement initiatives are often determined based on the experience and the judgements of experts (Cudney and Elrod, 2010; Wong and Wong, 2011b). It is important to note that the judgements of experts involve uncertainty. This is due to the natural variability between experts. Each expert has his/her own experience, speciality, attitudes and skills. To overcome such uncertainty, fuzzy logic can be adopted (Asan *et al.*, 2004). In the real situation, any problem attributes are often interrelated and have dependent interrelationship. This nature complicates the problem of presenting a faultless plan. According to Tseng and Lin (2009), fuzzy-decision making trial and evaluation laboratory (fuzzy-DEMATEL) method has the capability of analysing the interrelationship between system criteria and prioritizing the most important one(s), under the uncertain judgement of experts. Accordingly, research questions are highlighted as follows:

RQ1. How can industrial firms use TOC with balanced scorecard (BSC) to accurately diagnose the manufacturing system and understand its real constraints?

RQ2. How can industrial firms select the appropriate lean tools that can be used in eliminating or reducing the effect of the defined bottlenecks?

RQ3. How can industrial firms prioritize the selected lean tools considering their interrelationships and the uncertain judgement of experts; and then develop the required performance improvement road map?

Responding to such problems, this work aims at developing a structural model for developing a lean improvement plan for industrial firms. First, relying on the predefined business objectives, the operational objectives can be set using the BSC. Afterwards, TOC is introduced to determine the manufacturing system constraints that restrict the system from achieving the operational objectives. FTA is used to discover the root causes of those constraints in a structured procedure. Corresponding to these root causes, the appropriate lean improvement tools are proposed using the experts' judgement. Finally, the fuzzy-DEMATEL method is used to overcome the uncertainty of experts' decisions during the prioritization of the selected improvement initiatives. Accordingly, the suitable lean improvement road map can be developed based on the experts' knowledge and the interrelationships between the lean tools.

Although many surveys have illustrated trends and widely applied improvement tools (Charlesworth, 2000 and Bain and Company, 2019), there is a limited number of models in the literature addressing rational decision criteria for selecting and prioritizing improvement initiatives. This gap provides a high motivation to develop a model that supports selecting and prioritizing the lean improvement initiatives. Relies on system diagnosis using TOC, lean initiatives can be proposed and selected. Moreover, the fuzzy-DEMATEL method can be used to manage experts' knowledge and prioritize those initiatives. Consequently, a lean improvement road map can be developed and implemented. The proposed technique is implemented in a medium manufacturing firm operating in Egypt and results indicate the effectiveness of the proposed technique in achieving the predefined business strategic objectives.

The remainder of this paper is organized as follows: the literature review of the related works is presented in Section 2. In Section 3, the proposed approach with the fuzzy-DEMATEL method is explained in detail. Section 4 presents the real case study that is used to test the effectiveness of the proposed methodology. The results are discussed in Section 5. Finally, Section 6 represents conclusions and perspectives.

2. Literature review

Usually, manufacturing experts face a challenge of cascading strategic goals into applicable operational actions. Many researchers, including Hill (1989) and Platts and Gregory (1990), established frameworks to translate firms' objectives into actions. Vickery (1991) also suggested a generic model that started by identifying the competitive priorities based on the business strategy, defining the manufacturing objectives and finally deciding on the suitable initiatives. Kim and Arnold (1996) proposed a linkage method to select suitable initiatives based on a survey of 200 questions to manufacturing managers. Tan and Platts (2000) developed a framework using the analytical hierarchy process to determine the appropriate actions based on the understanding of the manufacturing environment. Their methodology illustrates the relationship between initiatives and objectives that rely on the managers' judgement regardless of studying/analysing the uncertainty due to different managers' experience. The importance of linking business strategic objectives to the operational level was also highlighted by Nielsen and Nielsen (2012) and Jung *et al.* (2015). Whereas analysing the interrelationship between the selected operational initiatives and prioritizing them based on their importance for achieving the strategic goals were not considered. Moreover, Table I summarizes some studies that integrate lean with different methods.

Kaplan and Norton (1992) developed the BSC, which aims to demonstrate the strategic objectives in a hierarchical system using four perspectives (financial, customer, internal processes and learning and growth). BSC is launched by the strategic objectives and aligned towards the financial perspective, then the causal interrelationship of the cascaded objectives is developed starting from the financial aspects, passing through customer perspectives and internal process goals, until it reaches learning and growth goals (Kaplan and Norton, 1996). Although it was reported by Alloghani *et al.* (2017) and Vieira *et al.* (2017), that BSC is adopted to enhance the strategic planning process and establish the performance measurement system in small and medium enterprises, the linkage between strategic objectives and operational initiatives is very difficult to be elaborated without good practical experience. Hudson *et al.* (2001), Kanji (2002), Mohobbot (2004) and Akkermans and Van-

Table I.
Several studies that integrate lean with other method

Previous studies	Adopted approach and findings
Pacheco *et al.* (2018)	Integrating lean and TOC in operation management to enables decision makers and industrial managers to evaluate improvement practice adopted in the production field
Swink *et al.* (2005)	Concluding that integration of strategies serves as a basis for improved cost efficiency and new product flexibility
Dave and Sohani (2019)	Developing a model in which lean practices can be grouped or bundled for optimizing industries overall performance
Moya *et al.* (2019)	Introducing a new framework to support lean six sigma deployment in Small and medium enterprises (SMEs), this framework allows SMEs to understand their strengths and weakness by using analytic hierarchy process
Sraun and Singh (2017)	Using continuous improvement strategies, including redesign, suggestion system and process flow mapping for achieving manufacturing performance improvement and improving product quality
Behrouzi and Wong (2011)	Using fuzzy logic for evaluating of lean performance of manufacturing system
Susilawati *et al.* (2015)	Using fuzzy logic to measure the degree of progress of lean activity
Vinodh and Kumar Chintha (2011)	Using fuzzy logic for enabling leanness in manufacturing system

Oorschot (2005) concluded that one of the weak points of BSC is the lack of integration between the top and operational levels that may lead to failure of achieving the desired goals. Besides, manufacturing systems constraints are not considered during cascading objectives into measures or initiatives. Therefore, the current work proposes to use TOC for diagnosing the manufacturing system and to clearly define its bottlenecks that impede the achievement of targets. Goldratt and Cox (1984) introduced TOC with the introduction of optimized production timetables scheduling software. The concept of TOC according to Goldratt (1988) can be identified as follows: every system must have at least one constraint. Constraints usually restrict the manufacturing system from achieving higher performance. The existence of constraints represents opportunities for improvements. A gradual elevation of constraints improves performance. Relying on this concept, the selected improvement initiatives should be focused on eliminating system constraints. Goldratt (1988) concluded also that all activities within a firm can be measured by using only three operational measurements: throughput, inventory and operational expenses. Later on, Goldratt and Cox (1992) introduced the seven focusing steps of TOC for determining systems constraints as follows: define goals of the system, determine proper and simple measures of performance, identify the constraints which restrict the system from achieving goals, eliminate root causes of constraints, smooth workflow and avoid building-up inventory within the system, assess the constraints and go to step one for another continuous improvement cycle. Scheinkopf (1999) described these steps as the prerequisite for any improvement process. Adopters of TOC such as Johnson (1986) and Koziol (1988) reported that TOC could result in increasing throughput and decreasing inventory concurrently with reducing manufacturing expenses. Also, Klein and Debruine (1995) and Olson (1998) pointed out that TOC has developed rapidly not only as a philosophy but also as an improvement methodology. Mabin and Balderstone (2003) also concluded that TOC can be adopted to determine bottlenecks and to suggest directions to reduce/eliminate their effect. Moreover, organizations applying TOC gained considerable improvements in performance measures such as lead-time, cycle-time and revenue (Şimşit *et al.*, 2014; Dalci and Kosan, 2012). Relying on Watson *et al.* (2007), TOC has been adopted by about 500 companies, including 3 M, Boeing, Ford Motor Company, General Electric and General Motors because of its capability to provide a source of competitive advantage. Coetzee *et al.* (2016) used TOC to improve the productivity of telescope operations by understanding and finding the bottleneck processes. Moreover, TOC enhances making sensible decisions that are in alignment with corporate goals because understanding constraints root causes is the first step to select the right improvement initiatives (Smith, 1999). A good literature review of TOC is presented in the work of Kim *et al.* (2008) and Şimşit *et al.* (2014).

Constraints root causes are often interrelated. Consequently, their associated lean tools are likewise interrelated. Relying on Lin and Wu (2004), the DEMATEL method can convert the interrelationship among causes and effects of criteria into a structural model. In addition, Sun (2015) used DEMATEL to identify and prioritize the critical success factors in electronic design automation. Lin and Wu (2004) pointed out that human judgements with preferences in the DEMATEL are often unclear and hard to express by crisp numerical values, and this created the need for fuzzy logic to be integrated with DEMATEL. Fuzzy logic allows researchers to incorporate easily various experts' decision to find the impact among model factors (Zimmermann, 2011). Besides, Chang *et al.* (2011) used fuzzy-DEMATEL method to define the causal interrelationship between factors of suppliers selection. Wu and Lee (2007) pointed out that fuzzy-DEMATEL could address problems with complex interdependent factors with uncertainty. Fuzzy-DEMATEL was also validated by the work of Tseng (2010) in presenting a perception approach to deal with service quality categorizing with uncertainty, as well as the work of Lin and Wu (2008) and Patil and Kant (2013).

Implementation of lean manufacturing was successfully applied in a variety of industries and had a profound impact (Gupta *et al.*, 2019). For example, it was applied in aerospace industries, computer and electronics manufacturing, forging company (Lander and Liker, 2007), automotive manufacturing and steel industries (MacDuffie *et al.*, 1996). Moreover, many researchers adopted lean concepts and achieved encouraging results. Tinoco (2004) reduced work in process (WIP) by constructing the VSM for a family of resonators. VSM allowed the company to document and monitor lead-time, inventory levels and cycle times. Högfeldt (2005) increased overall equipment effectiveness (OEE), by developing the VSM and identifying all types of waste before starting the applications of the total productive maintenance. Talip *et al.* (2011) reduced excessive transportation time in fishery products factory by renovating the layout and reducing the number of working cells from eight to five. The use was also improved from about 61.4 per cent to about 81.8 per cent due to work standardization. Rajenthirakumar and Thyla (2011) improved productivity in an automotive components manufacturing company using Kaizen. They found that 101 ss were value-added activities compared to 80,640 s of non-value-added activities. After applying Kaizen and single minute exchange dies, the change over time during the bending process was reduced from 2,815 to 755 s. In addition, the setup time during squeezing operations was reduced from 2,600 to 580 s. Oscar and Twentiarani (2012) improved an assembly line after reducing the variability of standard time by redesigning the work arrangements among the operators through line balancing methods. Line efficiency was increased from 57.6 to 92.4 per cent. Sheth *et al.* (2012) improved the productivity of an automobile assembly line from 120 to 145 vehicles per day after line balancing. Also, after reducing waste, manpower utilization was increased from 60 to 80 per cent, and the total number of operators reduced from 69 to 58. Moreover, the work of Goshime *et al.* (2019) presents that adopting lean manufacturing leads to improvement of productivity and many successful stories of lean implementation are summarized in Table II.

The successful works of Arya and Jain (2014), Arya and Choudhary (2015), Alvarez *et al.* (2017), Gupta and Gupta (2017), Kumar *et al.* (2018a, 2018b), Garza-Reyes *et al.* (2018) and Chouiraf and Chafi (2018) illustrate that each firm need special lean improvement to improve its performance, and the firm's experts should decide which initiatives need to be implemented and in which order.

3. The proposed model

The proposed methodology integrates BSC, TOC, FTA and fuzzy-DEMATEL method. The model is developed based on the concept of the process approach, where the input is the strategic objectives, whereas the output is the lean improvement road map. Figure 1 illustrates the proposed model. In the following sub-sections, the different steps of the proposed model are discussed in detail.

3.1 Balanced scorecard and operational objectives

BSC is developed to monitor firm performance against strategic objectives through the enhancement of the predefined measures. As shown in Figure 1, the strategic objectives are considered as the input to the proposed model, the first step is to convert these goals into operational objectives. For example, increasing market share can be converted into reducing manufacturing cost. This conversion process is considered as a drill-down process, for which the concept of FTA is suggested. To illustrate this process, for the strategic objective of increasing market share, the concept of FTA can be used to

Previous studies	Field of application	Adopted approach	Findings of the study
MacDuffie *et al.* (1996)	Steel industries Automotive manufacturing	Lean tools	Lean production plants are capable of handling higher levels of product variety with a less adverse effect on total labour productivity than traditional "mass production" plants
Tinoco (2004)	Resonators industries	VSM	Reducing WIP
Högfeldt (2005)	Industrial plant	VSM Waste identification Adopting of total productive maintenance	Increasing OEE
Lander and Liker (2007)	Aerospace industries Computer and electronics manufacturing Forging companies	Using one-piece flow cells Controlling buffers by pulls signals	Reducing buffers size
Talip *et al.* (2011)	Fishery product factory	Renovating the layout Using of manufacturing cells instead of assembly line	Reducing transportation time Improving labour use
Rajenthirakumar and Thyla (2011)	Automotive components manufacturing company	Kaizen implementation	Increasing productivity Reducing lead time Reducing dies changeover time
Oscar and Twentiarani (2012)	Assembly line	Improving labours' skills Redesigning the work arrangements among operators Adopting line balancing methods	Reducing standard time variability Improving assembly-line efficiency
Swaroop *et al.* (2012)	Automobile assembly line	Balancing of the assembly line Using of Yamazumi chart Reducing waste	Improving productivity Improving manpower use Reducing motion and transportation time
Arya and Jain (2014)	Small-scale Indian industries	Integration of Kaizen with VSM	Reducing of process time Reducing working area Improving lead time
Arya and Choudhary (2015)	Small-scale Indian industries	Kaizen implementation integrated with ISO as a quality management system	Reducing transportation time Reducing lead time Clean working area
Swarnakar *et al.* (2018)	Automotive component manufacturing organization	Lean tools	Reducing defects Increasing production rate Decreasing changeover time
Alvarez *et al.* (2017)	Footwear company	integrating lean with the TOC	Reducing inventory Reducing non-value-added time
Kumar *et al.* (2018a, 2018b)	Small-to medium-scale enterprise in India	Waste elimination Kaizen implementation VSM analysis	Reducing inventory Reducing cycle time Improving product quality
Chouiraf and Chafi (2018)	Handicraft production	Integrate of lean manufacturing in handicraft organizations	Lean tools successfully applied in handicraft organizations

Table II.
Successful lean application studies

convert it into two operational objectives improving production rate and reducing production cost (marketing initiatives are not considered here). A suitable measure should be then assigned to each operational objective. These measures are known as key performance indicators (KPIs). Traditionally, operational actions can be decided for achieving each operational objective.

3.2 Manufacturing system analysis

Operational initiatives listed in the BSC cannot be achieved easily without reducing the effect of the system constraints. Hudson *et al.* (2001), Kanji (2002), Mohobbot (2004) and Akkermans and Van-Oorschot (2005) pointed out that manufacturing systems' constraints are not considered during cascading strategic objectives into operational initiatives. Relying on this fact, this work proposes to diagnose the manufacturing system after defining the operational objectives to highlight the system constraints. According to Goldratt (1988), the three measures of TOC are used for this purpose: throughput, WIP and operational expenses. In addition, historical data analysis should be performed to determine problems' symptoms. Afterward, the major root causes behind each constraint can be searched using FTA and historical data analysis. Once root causes are emphasized, the experts can propose the most appropriate initiatives that eliminate/reduce the constraints' effect. For example, in the manufacturing process of refrigerators, if the desired objective is to increase the daily production rate, the historical data related to the weakness of the production system should be collected and analysed. Suppose that the production rate is low due to two reasons:

(1) long dies exchange time of refrigerator outer shell forming machine; and
(2) a high rate of nonconformities of inner liners during the thermoforming process.

By drilling down behind these factors (using both historical data analysis and expert's knowledge), the complete FTA diagram can be developed as shown in Figure 2. FTA shows how these causes interact with each other, e.g. reasons (A) and (B) are independent, i.e. the occurrence of any one of them leads to high dies exchange time. Contrary, the "variation in plastic sheet thickness" and "lack of labour experience" should occur together to produce a "high rate of nonconformities of products".

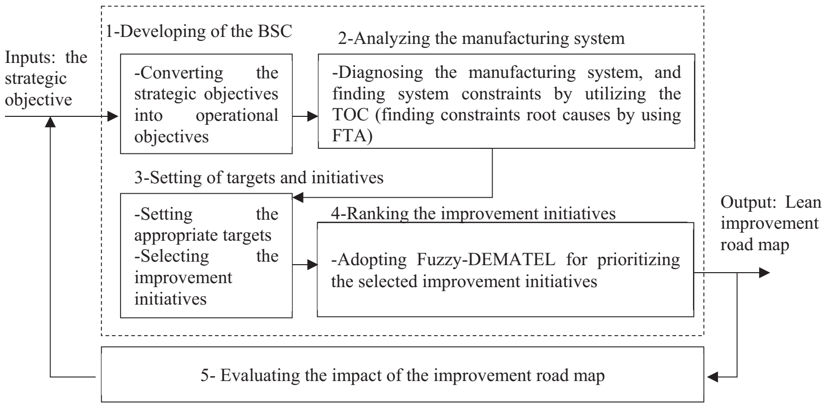

Figure 1.
The proposed model to convert strategic objective into improvement road map

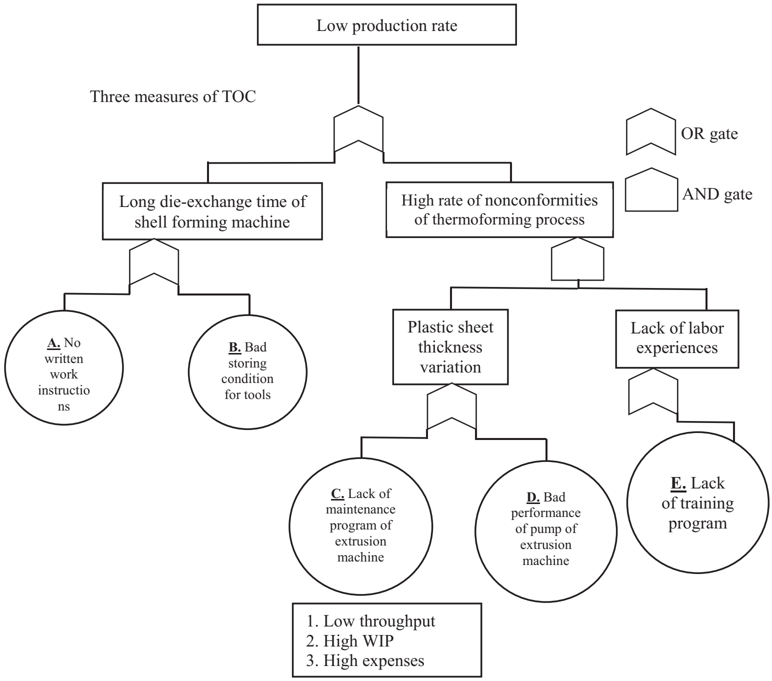

Figure 2.
Determining constraints' root causes using FTA

3.3 Identification of lean improvement tools

Subsequently to the identification of constraints' root causes, lean improvement tools can be proposed. Accordingly, the related KPIs can be set accurately. The determination of improvement initiatives depends on operational experts. Focus group meetings should be organized to generate ideas about the needed initiatives and evaluate their impact on KPIs. Experts should use historical data and statistical tools together with their experience to figure out the impact of lean initiatives. For example, relying on Figure 2, two KPIs can be set, namely, KPI-1 (reduction of dies exchange time by a specified percentage) and KPI-2 (reduction of part nonconformity by a specified percentage). In addition, the following set of lean initiatives can be considered as improvement actions: executing appropriate training, standardize the work instructions of die exchange process, applying 5Ss steps to arrange tools and jigs, performing periodic based maintenance on sheet extrusion machine. Table III presents the constraints' root causes, and the suggested lean initiatives to reduce their effect for the example provided. The company experts evaluate the impact of lean initiatives on KPIs during focus group meetings. To figure out the strength of this impact, a three-level scale is used (null, moderate and very high). Conventionally, the tactic with the greatest impact should be implemented first. Nonetheless, this study suggests prioritizing those initiatives based on the analysis of their interrelationships.

3.4 Prioritization of improvement initiatives

To prioritize the proposed lean tools, the fuzzy-DEMATEL method is adopted. This adoption relies on two main reasons. The first is the capability of the DEMATEL method to

Constraints	The constraints causes	Suggested lean initiatives	Impact of initiatives on KPIs KPI-1	KPI-2
Long die exchange time of outer shell forming machine	No written procedures or work instructions for dies exchange work	Preparing and reviewing a work instruction sheet that illustrates how to exchange dies in standard steps	Very high	Null
	Bad arrangements of tools and jigs	Applying 5Ss program	Very high	Moderate
High rate of nonconformities during the thermoforming process	Lack of maintenance of sheet extrusion machine	Performing a periodic based maintenance to the screw of the extrusion machine	Null	Very high
	Bad performance of the sheet extrusion machine's gear pump	Performing a conditional based maintenance for the machine gear pump	Null	Very high
	Lack of training program	Performing a skill-matrix and executing a periodic training on work and maintenance instructions	Very high	Very high

Table III. System constraints and the suggested initiatives for the illustrative example

convert the interrelationship among problem attributes into a structured model (Lin and Wu, 2004; Malviya and Kant, 2014). The second is the capability of the fuzzy logic to overcome the uncertain judgement of experts (Tseng and Lin, 2009). In the beginning, it is proposed to present the procedures of DEMATEL method with crisp numbers by the following steps:

- *Step 1*: Collect different improvement initiatives. Identify the evaluation scale that represents the interrelationship among improvement initiatives, e.g. zero to four scale can be used, where zero represents no interrelationship and four represents a very-high interrelationship.
- *Step 2*: Establish the "Direct Relation Matrix": a set of experts are asked to evaluate the level at which initiatives influence each other. An (N × N) matrix is produced by each expert, where N is the number of initiatives. To incorporate the opinions of all experts, an average matrix is constructed (known as direct relation matrix). In this matrix, each element (a_{ij}) indicates the degree by which initiative i influences initiative j.
- *Step 3*: Calculate the normalized direct relation matrix *(D)*, by dividing each element in the direct relation matrix by the matrix's largest row sum.
- *Step 4*: Calculate the total relation matrix *(T)*: $T = D \times (I - D)^{-1}$, where: ($I$) is the identity matrix. Calculate the sum of ith row in T-matrix (R_i) that indicates the effect given by initiative i on others. Calculate the sum of jth column in T-matrix (C_j) that specifies the effect received by initiative j from others. The degree of importance and the net effect can be computed respectively as ($R_i + C_j$), and ($R_i - C_j$) for each $i = j$.

To overcome the uncertainty of experts' decisions fuzzy-DEMATEL is adopted. The fuzzification of experts' decisions relies on the membership function used, e.g. trapezoidal, triangular or any other shapes. In this work the model introduced in the work of Wu and Lee (2007), Chang *et al.* (2011) and Kabak *et al.* (2015) with the triangular fuzzy number is followed. In this model, a triangular fuzzy number $\tilde{A}$ is characterized as a trey (l, m, r) and the membership function, $\mu_{\tilde{A}}$ of this number can be defined as the following:

$$\mu_{\tilde{A}}(x) = \begin{cases} 0 & x < l \\ (x-l)/(m-l) & l \le x \le m \\ (r-x)/(r-m) & m \le x \le r \\ 0 & x > r \end{cases}$$

The fuzzy-DEMATEL method starts by applying exactly Step 1 of the DEMATEL method. After having an (N × N) matrix of crisp evaluations from every expert, these crisp evaluations are then fuzzified using a triangular fuzzy membership function. Subsequently, aggregate the n fuzzy decision matrices into an average fuzzy matrix according to equations 1 to 4 as proposed by Kabak *et al.* (2015):

$$\tilde{e}_{ij} = (l_{ij},\ m_{ij},\ r_{ij}) \cong Aggregation\ \left(\tilde{e}_{ij}^{n},\ n = 1, \ldots,\ N\right), \tag{1}$$

where:

$$l_{ij} = \min_{n=1,\ldots,\ N} l_{ij}^{n}, \tag{2}$$

$$m_{ij} = \sum_{n=1}^{N} m_{ij}^{n}/N \tag{3}$$

$$r_{ij} = \max_{n=1,\ldots,\ N} r_{ij}^{n}. \tag{4}$$

Then apply equations 5-11 for the "defuzzification" process of the obtained matrix $\tilde{e}_{ij} = (l_{ij},\ m_{ij},\ r_{ij}\ )$.

Normalization:

$$xr_{ij} = \left(r_{ij} - \min\ l_{ij}\right)/\Delta_{min}^{max} \tag{5}$$

$$xm_{ij} = \left(m_{ij} - \min\ l_{ij}\right)/\Delta_{min}^{max} \tag{6}$$

$$xl_{ij} = \left(l_{ij} - \min\ l_{ij}\right)/\Delta_{min}^{max}, \tag{7}$$

where

$$\Delta_{min}^{max} = \max r_{ij} - \min l_{ij}.$$

Compute right (rs) and left (ls) normalized values:

$$xrs_{ij} = xr_{ij}/\left(1 + xr_{ij} - xm_{ij}\right) \tag{8}$$

$$xls_{ij} = xm_{ij}/\left(1 + xm_{ij} - xl_{ij}\right). \tag{9}$$

Compute total normalized crisp values:

$$x_{ij} = \left[xls_{ij}\left(1 - xls_{ij}\right) + \ xrs_{ij} \times xrs_{ij}\right] / \left(1 - xls_{ij} + xrs_{ij}\right) \tag{10}$$

Compute crisp values:

$$Z_{ij} = \min\ l_{ij} + x_{ij} \times \Delta_{min}^{max}. \tag{11}$$

With crisp values, the normalized direct relation-matrix D can be computed by dividing each element by the maximum value of all rows summation:

$$D_{ij} = Z_{ij} / \max_{1 \leq i \leq Ta} \sum\nolimits_{j=1}^{Ta} Z_{ij}. \tag{12}$$

Calculate the total relation matrix (T): $T_{ij} = D_{ij} \times (I - D_{ij})^{-1}$, where (I) is the unity matrix.

Calculate summation of each row in T:

$$R_i = \sum\nolimits_{j=1}^{Ta}\ T_{ij}\ \forall\ i = 1 \ldots ta \tag{13}$$

Calculate the summation of each column T:

$$C_j = \sum\nolimits_{i=1}^{Ta}\ T_{ij}\ \forall\ j = 1 \ldots ta \tag{14}$$

Relying on the impact given (R_i) and the impact received (C_j), the degree of importance for each initiative ($R_i + C_j$), and net effect ($R_{\mathrm{i}} - C_j$) can be computed. Based on the degree of importance and the net effect, the importance of each initiative can be quantified. In addition, the influence of initiatives on each other is determined. In this work, the improvement plan is constructed and started by considering initiatives with the highest importance relying on ($R_i + C_j$), and ($R_{\mathrm{i}} - C_j$). The authors suggest classifying initiatives into three implementation phases: The first phase contains initiatives with high ranks of (R_i+C_j) and ($R_{\mathrm{i}} - C_j$). The firm should start applying these initiatives immediately to accelerate achieving the desired goals. The second level represents initiatives with moderate importance, i.e. initiatives with low levels of ($R_i + C_j$) or ($R_{\mathrm{i}} - C_j$). Finally, the third phase contains initiatives with low levels of ($R_i + C_j$) and ($R_{\mathrm{i}} - C_j$).

3.5 Evaluation and control

During the implementation of the lean improvement road map, results should be monitored and evaluated periodically. The impact of the proposed initiatives on achieving the strategic objectives should be discussed and evaluated. If the improvements are not satisfying the organization's needs, another loop should be implemented, i.e. re-analyse the operational objectives, re-diagnose the production system, identify system's new constraints, propose lean initiatives, implement initiatives and monitor results. This continuous process of performance improvement planning can be considered as a continuous process of enhancement or simply a "plan-do-check-act" (PDCA) process.

4. Case study

The proposed approach was implemented at a home appliance firm located in Egypt (because of confidentiality, the company's name is not stated). More specifically, the model is used to determine and manage improvement initiatives in one of the firm's plants specialized in refrigerator manufacturing. In this plant, the manufacturing system consists of two main assembly lines, one to produce the refrigerator cabinet and is considered as the main assembly line while the second is dedicated to producing the refrigerator doors. A refrigerator can be assembled as soon as its cabinet and door(s) are manufactured, then it can be tested. Finally, the refrigerator is packed. Besides the previous assembly lines, there are some departments for manufacturing all parts such as pipes, metal pieces and plastic parts, considering that the compressor is outsourced. The main assembly line consists of four main workstations as follows:

(1) *Pre-assembly workstation*: The refrigerator outer shell is formed and assembled with the plastic inner liner, pipes of the cooling circuit and electrical wires.
(2) *Polyurethane injection workstation*: Inject the polyurethane liquids between the metal outer shell and the plastic inner liner, and then these liquids solidify and act as an isolation layer between the refrigerator inside portion and the outer environment.
(3) *Assembly workstations*: The compressor is assembled, the refrigerant is charged inside the cooling circuit, shelves are set inside refrigerator cabinet and finally doors are mounted with the cabinet.
(4) *Testing and packing workstations*: performance tests and visual checks are performed; repairing of non-conformities is done if any. Accordingly, only good products should be packed and shipped to distributors.

4.1 Identification of system constraints

After constructing the strategy map, the strategic business objective in the BSC was decided to be "increasing sales plan by 50 per cent before 2017". The BSC is then used to translate this strategic objective into an operational objective that is decided to be "increasing production rate by the same percentage of increasing sales". To increase the production rate by 50 per cent, the firm needs to develop a lean-based improvement road map that supports this challenge during 2016. Responding to that, the firm planned to adopt the proposed approach at the beginning of 2016. The model implementation was started by diagnosing the manufacturing system to discover its constraints. System diagnosing is done based on the three measures of the TOC as presented in section 3.2. For this purpose, a workshop is held with the factory experts to determine system constraints by using FTA diagram as represented in Figure 3, which translates the reasons of lack of TOC measures into real bottlenecks as follows:

- Low throughput is caused by time losses resulted from the increased waiting time, the excessive transportation/preparation and the excessive movements of labours. These time losses cause the symptom of unbalanced assembly workstations. Another reason is the lack of efficient material flow between inventories and assembly line that produces considerable idle times due to unavailability of components.
- Relatively high WIP inventory is observed because of the following reasons: high dies exchange time of door forming machine, unsatisfied quality rate of cabinet thermoforming machine that leads to making buffer storage after this machine and sudden failures of polyurethane machine. Accordingly, the production engineers tend to increase WIP to maintain the flow of the assembly line in case of machine downtime.

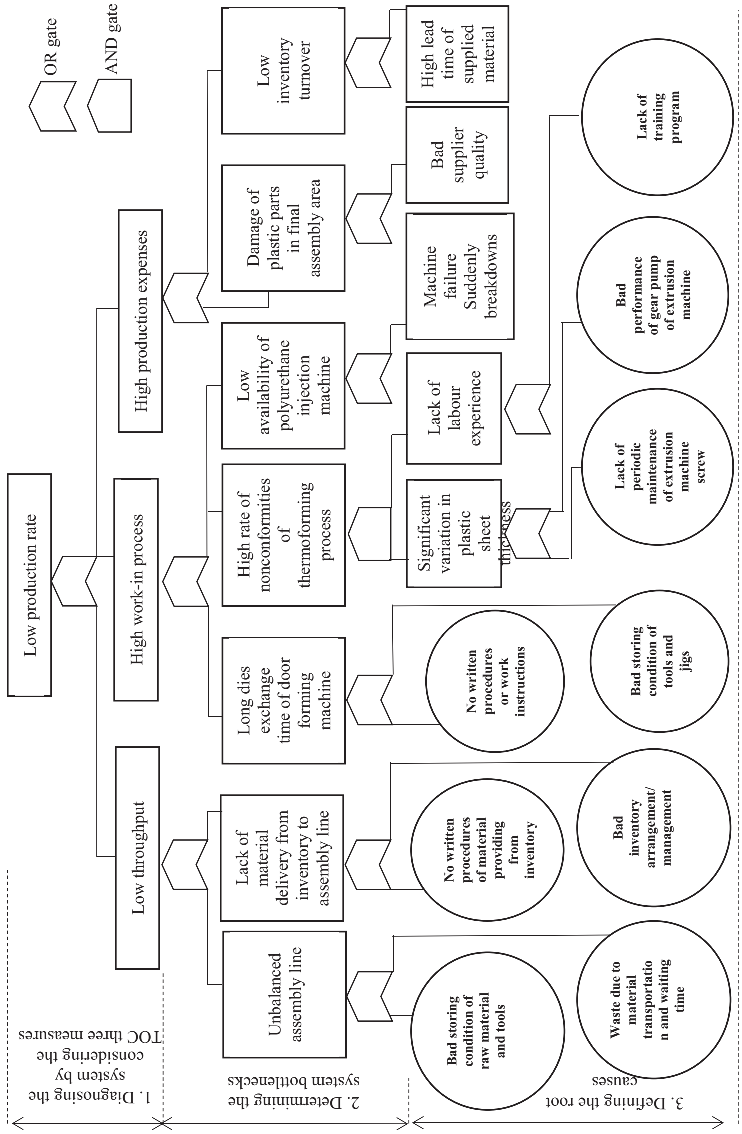

Figure 3.
Illustration of the system constraints and their root causes using FTA

- Increasing operational expenses resulted from increasing raw material used (compared with the bill of material); this difference is induced from the increased scrap. Another reason is the low inventory turnover (ITO) (four times per year) that is caused by a high inventorying strategy of the company.

Succeeding in performing factory diagnosis that highlights system constraints, the BSC can be developed (Table VI). These KPIs focus on the investigated constraints and have been used to measure the progress of applying the proposed methodology. The target values of each indicator are established in cooperation with the operational experts' committee. In addition, these target values were assessed based on the understanding of the difference between the common and assignable causes.

4.2 Root causes of system constraints

Ten experts were recruited from different factory departments (quality, maintenance and assembly department). Each expert has at least seven years of working experience in the factory, also each expert received a training course about lean manufacturing tools and principles. Relying on a workshop held with these experts, the root causes of each constraint were determined and synthesized in an FTA diagram (Figure 3) and summarized as follow:

(1) *first indicator*: assembly line balancing efficiency:
   - lack of raw material, components and tools arrangement inside workstations;
   - lack of standardization for assembly operations that cause waiting time loses;
   - lack of direct labour skills; and
   - variation of staffing level between working shifts.

(2) *second indicator*: material flow among inventories and workstations:
   - poor arrangement of inventories; and
   - no clear instructions about the material delivery process.

(3) *third indicator*: die exchange time:
   - lack of standardization for die exchange operations;
   - lack of tools arrangement;
   - hidden failure of die-exchange machine features; and
   - lack of standardization for maintenance operations of die-exchange machine features.

(4) *fourth indicator*: quality rate of cabinet liner thermoforming machine:
   - lack of plastic sheet quality which supplied from the external supplier;
   - lack of direct and maintenance labor skills;
   - lack of performing preventive maintenance such as cleaning, tightening, and lubricating and other routine maintenance work; and
   - lack of machine conditions monitoring such as vibration, lubricant and temperature.

(5) *fifth indicator*: availability of polyurethane machine:
   - lack of direct and maintenance labor skills;
   - lack of monitoring of machine parameters; and
   - lack of analysis to understand and define each failure root cause.

(6) *sixth indicator*: quality rate of injected plastic parts:
- lack of handling and transportation equipment;
- lack of packing methods; and
- lack of quality control and supervision in the plastic suppliers' workshop.

(7) *seventh indicator*: ITO:
- long replenishment lead-time from external suppliers; and
- high inventory levels.

4.3 Identification of lean improvement tools

After identifying the root causes behind constraints, the associated lean improvement initiatives can be decided. Each initiative can have an associated contribution to one or more KPIs. To assess these contributions, brainstorming three workshops are organized and attended by the previous ten operational experts with the current authors. To evaluate the contribution of the proposed performance initiative on achieving the specified KPI, experts used the five-point scale in which (0 = no impact, 1 = weak impact, 2 = moderate impact, 3 = high impact, 4 = very high impact). The obtained improvement initiatives and their associated impact on the different KPIs are listed in Table IV. The table illustrates the initiatives' impact on the KPIs with descending order. The authors and the experts observed

Suggested lean improvement initiativesinitiatives	Lean initiative symbol	KPI-1	KPI-2	KPI-3	KPI-4	KPI-5	KPI-6	KPI-7	Total
Using PDCA method of thinking with KAIZEN works	PT11	3	3	3	3	2	2	2	18
Providing 5S, lean principles, Kaizen and total productive maintenance training modules for direct, maintenance and warehouse labour	PT1	3	3	3	3	2	1	0	15
Standardizing inventory and operations work	PT4	2	2	3	2	2	1	1	13
Applying KANBAN supermarket system	PT5	3	3	0	0	0	3	3	12
Improve supplied material quality	PT13	2	1	0	2	0	3	3	11
Applying 5S system in inventories and workstations	PT2	1	2	2	1	1	3	0	10
Applying visual control in both inventories area and workstations	PT6	2	2	1	1	1	1	1	9
Reducing waste due to transportation, excessive motion and waiting	PT3	3	3	0	0	0	2	0	8
Improve supplied material handling and packing conditions	PT14	1	1	0	1	0	3	2	8
Using failure mode and effect analysis to reduce failures of polyurethane machine	PT7	1	0	1	1	3	1	0	7
Applying reliability centered maintenance principle	PT8	1	0	1	2	3	0	0	7
Using ABC analysis for inventory control	PT9	1	3	0	0	0	0	2	6
Reduce replenishment lead time (from supplier to factory warehouse)	PT12	0	1	0	1	0	1	3	6
Reduce both safety stock, and slow-moving inventory. Eliminate absolute stock	PT10	1	1	0	0	0	0	3	5

Table IV.
The proposed lean improvement initiatives and their impact on achieving KPIs

that it is not suitable to use this order during applying the proposed improvement plan. For example, it is not applicable to start Kaizen actions (PT11) before performing suitable training (PT1). In addition, it is not suitable to apply KANBAN (PT5) to improve material flow before performing 5S program (PT2) to sort, and set in order these materials inside the inventory and around workstations, and before applying visual control methods (PT6) to monitor the level of work in process. This observation motivates experts to prioritize the lean initiatives by understanding the interrelationship among them i.e. by using the fuzzy-DEMATEL.

4.4 Lean tools prioritization using fuzzy-decision making trial and evaluation laboratory

For managing and ranking the lean improvement initiatives, the selected ten experts are asked to assess the degree of influence between each pair of initiatives. First, each expert is given an empty template matrix (14 × 14) represents the initiatives as rows and columns, and then he/she was asked to fill-in his/her template by using the five-point assessment scale in crisp scores (0 = no influence, 1 = weak influence, 2 = moderate influence, 3 = high influence, 4 = very high influence). After collecting these matrices, the crisp rating is then fuzzified by converting crisp numbers to fuzzy numbers using the triangular membership function in which 0, 1, 2, 3 and 4 are replaced, respectively, by (0, 0, 0.25), (0, 0.25, 0.5), (0.25, 0.5, 0.75), (0.5, 0.75, 1.0) and (0.75, 1.0, 1.0). Subsequently, the fuzzy-DEMATEL model presented in section 3.4 is run after coded it in MATLAB software. Based on the total relation matrix obtained as listed in Table V, the effects that improvement initiatives exert (R_i) and receive (C_j), the degree of importance ($R_i + C_j$) and the net effect ($R_i - C_j$) are computed. Accordingly, the ranking of initiatives can be performed according to the cause and effect diagram (Figure 4), which represents ($R_i - C_j$) with respect to ($R_i + C_j$). The authors classify this plot into four areas:

- Area 1: represents the initiatives with a high degree of importance and high net effect;
- Area 2: represents the initiatives with a high degree of importance and low net effect;
- Area 3: represents the initiatives with a low degree of importance and low net effect; and

Initiatives	PT1	PT2	PT3	PT4	PT5	PT6	PT7	PT8	PT9	PT10	PT11	PT12	PT13	PT14	(Ri)	(Ri+Cj)	(Ri–Cj)
PT1	0.06	0.17	0.20	0.19	0.18	0.20	0.13	0.15	0.16	0.16	0.15	0.10	0.10	0.12	2.09	2.88	1.3
PT2	0.08	0.07	0.15	0.14	0.14	0.17	0.08	0.10	0.12	0.11	0.08	0.04	0.06	0.08	1.42	2.82	0.01
PT3	0.04	0.09	0.05	0.10	0.10	0.11	0.06	0.06	0.04	0.04	0.07	0.03	0.03	0.06	0.86	2.54	–0.83
PT4	0.08	0.13	0.14	0.08	0.14	0.15	0.06	0.09	0.09	0.10	0.10	0.09	0.06	0.10	1.41	2.87	–0.05
PT5	0.02	0.07	0.09	0.08	0.04	0.09	0.02	0.05	0.03	0.07	0.03	0.05	0.05	0.08	0.77	2.22	–0.68
PT6	0.09	0.11	0.15	0.12	0.11	0.08	0.04	0.11	0.09	0.10	0.08	0.07	0.04	0.08	1.25	2.97	–0.47
PT7	0.03	0.03	0.04	0.09	0.03	0.09	0.02	0.09	0.03	0.03	0.07	0.02	0.02	0.02	0.61	1.35	–0.13
PT8	0.06	0.04	0.07	0.10	0.04	0.10	0.07	0.04	0.04	0.08	0.07	0.03	0.03	0.03	0.79	1.83	–0.25
PT9	0.09	0.13	0.16	0.14	0.14	0.16	0.04	0.05	0.05	0.06	0.09	0.04	0.03	0.05	1.21	2.31	0.12
PT10	0.05	0.12	0.12	0.08	0.09	0.11	0.03	0.04	0.11	0.05	0.06	0.03	0.08	0.06	1.04	2.26	–0.18
PT11	0.10	0.16	0.17	0.15	0.16	0.18	0.11	0.15	0.12	0.14	0.07	0.09	0.09	0.11	1.79	2.80	0.78
PT12	0.03	0.11	0.11	0.11	0.08	0.10	0.03	0.04	0.07	0.11	0.06	0.03	0.10	0.06	1.04	1.72	0.36
PT13	0.03	0.08	0.10	0.05	0.09	0.08	0.02	0.03	0.07	0.10	0.06	0.06	0.03	0.04	0.82	1.62	0.02
PT14	0.03	0.10	0.12	0.06	0.10	0.10	0.04	0.05	0.07	0.10	0.03	0.02	0.08	0.03	0.94	1.85	0.03
(Cj)	0.79	1.41	1.69	1.46	1.45	1.72	0.74	1.04	1.09	1.22	1.01	0.68	0.80	0.91	–	–	–

Table V.
Total relation matrix (T) with the impact given and received

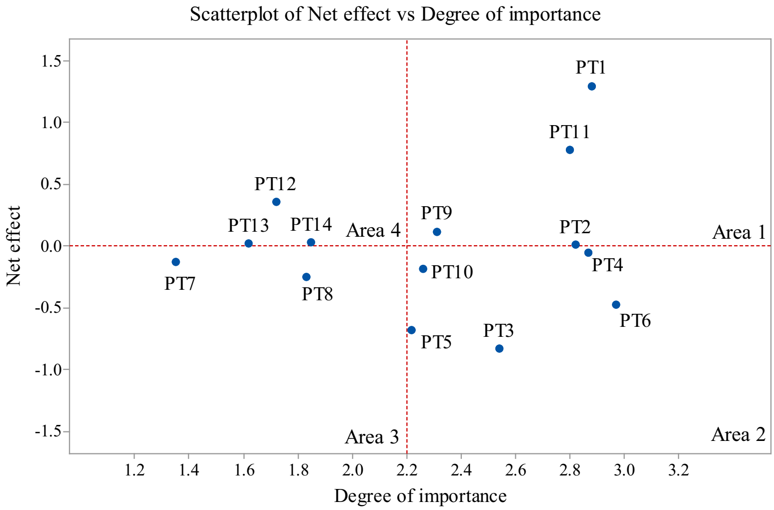

Figure 4.
Cause and effect diagram representing the net effect with respect to the degree of importance

- Area 4: represents the initiatives with a high net effect and low degree of importance.

Initiatives with negative net effect considered as the causes, whereas initiatives with positive net effect considered as effect (Figure 4).

Accordingly, the implementation plan of initiatives is constructed as shown in Figure 5 in which the first phase starts with the initiatives of area 1. Phase 2 contains all initiatives of Area 2 and Area 3. Moreover, Phase 3 contains all initiatives of Area 4. Sequentially, the Gantt chart was prepared; it represents the time-frame of applying the three phases of the improvement plan. To develop this chart, experts estimated the implementation time of each initiative. Moreover, they identified the sequence of initiatives implementation relies on the prioritization obtained from fuzzy-DEMATEL and the company resources. Furthermore, it is planned to execute this plan in 2016.

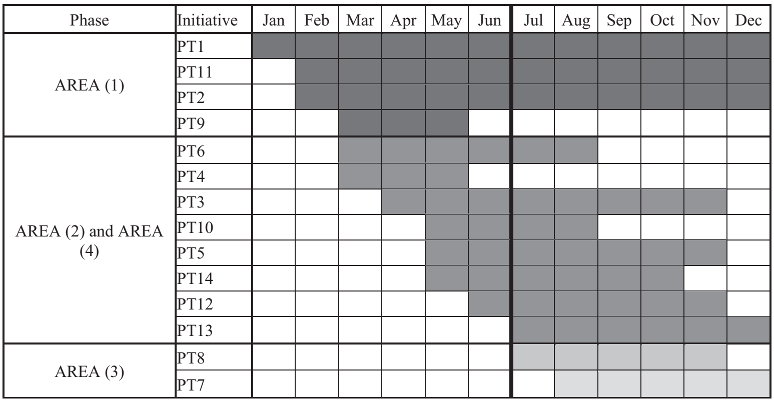

Figure 5.
Lean improvement road map

5. Results and discussion

The proposed lean improvement initiatives were implemented as scheduled in 2016. The following results were obtained by applying the three phases of the plan. The results as in Table VI were discussed and approved by the firm top management in March 2017. As shown in Table VI, the improvement of the line balancing efficiency exceeded the target. On the other side, there are some KPIs that need more improvements to reach the specified targets, e.g. the percentage of repaired/scraped products. It is reported that defects are reduced, as a result of improving labour skills. However, this reduction still requires more efforts. During the implementation process of the plan, the results were analysed monthly, the results of January 2016, July 2016 and January 2017 are presented as shown in Figure 6. During the first half of 2016, most of the adopted initiatives aimed at reducing variability, i.e. improving the stability of daily production rate. It is observed that the production rate was not stable in January 2016. On some days, production reaches 600 units/day and on other days, it reaches below 400 units/day. This variation was occurred because of the lack of standardization due to unavailable/unclear work instructions for working methods, lack of tools, inventory and workplaces arrangement and unbalancing of assembly workstations.

Relying on Figure 6, the stability and the value of the production rate are improved. For example, the production rate of July 2016 become more stable compared to that of January 2016 with an average increase of 17 per cent. During the second half of 2016, most initiatives were dedicated to improving material flow/delivery from inventory to workstations, eliminating stoppages due to machine breakdowns and increasing the quality of the supplied material. Consequently, the assembly line availability was improved and the production rate was increased from an average of 590 to 750 units/day (27 per cent increase). Finally, a comparison between the daily production rate of January 2016 and January 2017 shows that an improvement of 48.5 per cent was observed. This verifies that adopting the proposed improvement initiatives significantly increases the production rate. Another reason for these improvements is that the proposed methodology determines the success factors for the selected initiatives. Simply the success factors can be highlighted by observing the highest factors that the specified initiative is received. As example, Table V can be used to present the success factors of initiative PT8 (reliability-centred maintenance), respectively, are PT1: training of direct and maintenance labour, PT11: using PDCA cycle and KAIZEN activities, PT6: applying visual control methods, PT2: applying the 5S program and PT4: standardizing of maintenance and operations work. Moreover, investigating the causal relationships between initiatives and their success factors can support improvement plan management. Additionally, the relationship between the obtained results and the adopted initiatives can be documented and can be used during the continuous performance improvement cycle as a form of knowledge capitalization.

Another evidence for the effectiveness of the proposed methodology is the data received from the specialist of market research. They reported that the market volume was increased by about 5 per cent during the first quarter of 2017 compared with that of 2016. This result verifies that the proposed model succeeds in achieving the company's operational objectives and supporting the associated strategic objectives in a relatively short time. The adoption of the proposed methodology for lean implementation has a great influence on managerial implications by facilitating the process in a structural method. In other words, organizations that seek sustainable performance should define their strategic objectives. After that, those strategic objectives should be translated into operational objectives using BSC. As well known, the BSC is an effective tool for performance management. However, before setting the KPIs of the operational objectives, managers should consult their manufacturing systems to identify the system constraints or the hedges from improvement. The system constraints can be

Table VI. Manufacturing objectives and system KPIs status

BSC internal business objective	TOC	The constraints discovered	Indicators	KPI	Values in the beginning of 2016	Target values in Jan 2017	Actual values in Jan 2017	Status
Increasing of production rate by 50%	Throughput	Unbalanced manual assembly workstations	Assembly line balancing efficiency	I (1)	45%	90%	92%	Done
		Lack of material flow between inventories and assembly lines	Losses in planned times	I (2)	3.2%	0.0%	0.09 %	Accepted
	Inventory (WIP)	Long setup time of the door forming machine leads to increasing the WIP from different doors models (before door pre-assembly station)	Setup time	I (3)	180 min.	30 min.	25 min	Done
		Low-quality rate of the thermoforming machine which produces cabinet inner liners, leads to increasing the WIP before cabinet pre-assembly station	Part per million of nonconformity cabinet	I (4)	1.2%	0.2%	0.43%	On progress
		Low availability of polyurethane machine because of machine breakdowns	Mean time between failure	I (5)	8 h	24 h	23.6	Almost done
	Operational expenses	Low quality rate of final assembly stations due to damage in plastic parts (vegetable cases)	Part per million of nonconformity plastic parts	I (6)	0.95%	0.1%	0.25%	On progress
		Relatively low ITO (four times per year)	ITO per year	I (7)	4 times per year	6 times per year	5.6 times per year	Accepted

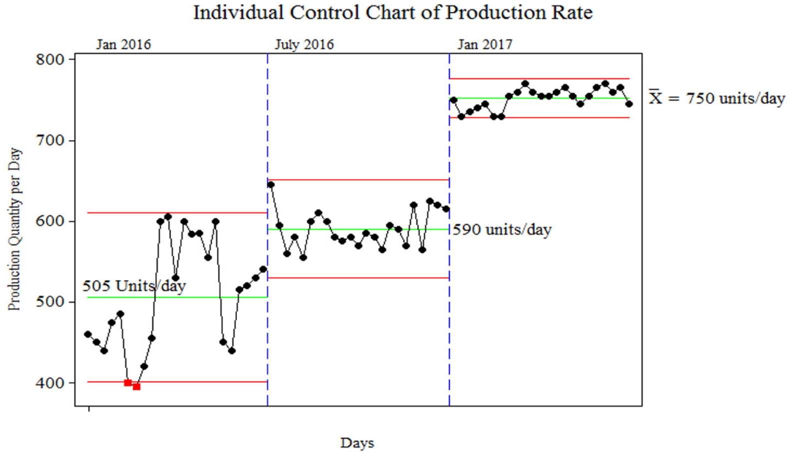

Figure 6. The effect of the proposed approach on the production rate improvement

identified by investigating the problems that negatively influence the three measures of TOC. For each constraint, the corresponding KPI can be set with the associated amount of improvement. To achieve such indicator, the root causes of the constraint should be investigated using a drill-down tool. For each root cause, the managers should select suitable lean initiative (s) that reduces the associated effect. It is well known that the lean tools are interrelated and one can support the outcomes of the others. To achieve great outcomes from the implementation of the lean project, managers should investigate the interrelationships between lean tools. The fuzzy-DEMATEL method is recommended to solve such problem. Moreover, the success factors of each tool should be identified before implementation. During the implementation of the lean project, the company should execute a package of managerial decisions such as forming cross-functional Kaizen team, setting relevant operational objectives and indicators in all working areas using live dashboards, establishing monthly rewarding and motivation system, performing monthly periodic meeting between top management and supervisors to continually control manufacturing system bottlenecks and monitoring KPIs. Adopting such managerial actions assures a sustainable performance improvement with a low probability of system resilience.

6. Conclusions and limitations

In this paper, an integrated approach is proposed to manage experts' knowledge and improve performance by selecting the appropriate lean manufacturing tools. It integrates BSC, TOC, FTA and the fuzzy-DEMATEL method along with experts' knowledge. Relying on the predefined strategic objectives, operational objectives can be set by using the BSC. Afterwards, the TOC is used to find the system constraints. For these constraints, the concept of FTA is used to determine the root causes of such constraints. Identifying root causes helps the experts to suggest suitable lean manufacturing tools. Then, the fuzzy-DEMATEL method is adopted to support prioritizing these tools considering their interrelationships and the uncertain judgement of experts. This classification of tools supports setting up the improvement action-plan. The plan presents the sequence of applying the selected tools and their implementation schedule. The proposed model is adopted in an Egyptian manufacturing firm, at one of its factories that dedicated to producing a family of refrigerators. The proposed improvement tools are selected based on the understanding of the manufacturing system bottlenecks. The results can be summarized as follows: increasing the production rate by 48.5 per cent in 12 months by determining and reducing the effect of the real system constraints. As perspectives of this work, the proposed model could be widely implemented in most of the Small and medium enterprises, as a result of the success of the proposed methodology. Another direction is to create a data bank that contains the organizational experience towards investigating the relationship between the strategic objectives and the operational lean initiatives. Another perspective is the development of an expert system that can produce an improvement plan relying on the diagnosis of the manufacturing system. This work is limited to manufacturing organizations. Besides, it reinforces the need for investigating the effectiveness of the proposed approach on service sectors, e.g. health-care sectors. In reasons of the subjective nature of manufacturing organizations, the impact of the proposed approach was contrasted by only comparing the performance before and after implementation. Consequently, it is worthy to investigate the impact of the approach on other case studies.

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Corresponding author
Sameh N. Seleem can be contacted at: samehnaeem100@gmail.com