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Investing in lean manufacturing practices: an environmental and operational perspective

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Lean manufacturing practices (LMPs) and corporate environmental sustainability are becoming inextricably linked. Throughout the lean and green debate, many organisations have recognised that LMPs have implications for their sustainable development and competitive positioning. Not only LMPs are complex on their own, but when perceived from an environmental sustainability perspective, the decision to implement an LMP can become even more intricate. Although general tools exist, the lack of effective decision-making tools to help in the implementation of LMPs with an environmental sustainability dimension is palpable. Thus, this study tackles the aforementioned decision problem by incorporating environmental and operational performance outcome expectations as these expectations are viewed in light of the ease of implementation of various LMPs. A novel multi-criteria decision-making (MCDM) model for evaluation of LMPs is developed in this respect. The model integrates a three-parameter interval grey number with rough set theory and the TODIM method. The model is run using empirical data from six manufacturing organisations. The findings facilitate the identification of a 'locus of investments' for a better selection of LMPs. The robustness of the decision support model developed is assessed through sensitivity analysis.

Keywords: lean manufacturing; environmental performance; operational performance; ease of implementation; rough set; TODIM; grey numbers

1. Introduction

Lean manufacturing practices (LMPs) have been of interest for organisational operational competiveness for decades (Dües, Tan, and Lim 2013). Key principles of LMPs include the identification and elimination of all non-value-added activities, or waste, and involve employees in efforts toward continuous improvement (Anand and Kodali 2008). Research on lean manufacturing suggests that while LMPs do not necessarily incorporate environmental responsibility, such practices can contribute to mitigate some of these environmental impacts because of their intrinsic focus on waste elimination (Bai, Dhavale, and Sarkis 2016). While LMPs may not have a direct intent to reduce environmental impact, their implementation had improved energy efficiency, reduced waste and emissions, and reduced inventory waste (Zhu, Johnson, and Sarkis 2018). A number of researchers have investigated the link between LMPs, operational (business) and environmental performance from an empirical and non-analytical perspective (Dües, Tan, and Lim 2013; Khanchanapong et al. 2014). The literature has reported mixed findings for the green and lean linkage. LMPs have both negative and positive effects on environmental performance, resulting in inconsistent and clouded results (Hajmohammad et al. 2013) LMPs occur upstream and downstream in the supply chain, for example, just-in-time (JIT) delivery by suppliers and lean supplier development (Bai and Sarkis 2016).

The complexity of various LMPs and the potentially large investment costs makes the implementation a multi-faceted and intricate task. While organisations recognise that LMPs have implications for their environmental sustainability and business performance, LMP implementation is difficult due to various operational complexities and lack of effective decision-making tools (Bai, Sarkis, and Dou 2015). In particular, a poor understanding of the relationship between the LMPs and operational / environmental performance and implementation practices contribute to the failure of LMPs (Bortolotti, Boscari, and Danese 2015). Thus, development of decision-making support tools can assist in LMPs performance appraisal, facilitating appropriate LMP oriented investment decisions given limited resources (Wu, Xu, and Xu 2016).

This study addresses this issue by developing an integrated model to assist organisations in choosing and investing in the best LMPs that simultaneously influence an organisation's operational and environmental performance (Dües, Tan, and Lim 2013). Few studies have sought to comprehensively investigate or introduce formal analytical models to evaluate and analyse

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the multiple aspects of LMPs implementation, including operational and environmental performance and the ease of implementation (Shah and Ward 2003). The relationship between LMPs and operational / environmental performance, as these correlate with organisational ease of implementation, would help address the ‘locus of investments’ for LMPs.

In order to advance lean manufacturing research, this study seeks to make the following academic and managerial contributions: (i) A novel multi-criteria decision-making (MCDM) model that integrates rough set theory, the TODIM[1] method, and three-parameter interval grey numbers is developed. (ii) Rough set theory and three-parameter interval grey number are used to overcome the limitations of the TODIM method to solve the MCDM problem considering decision maker’s (DM) opinions. (iii) Easily implemented LMPs that can improve operational and environmental performance are identified using an empirical example. In this regard, we used the judgmental input (through a formal survey) of a lean manufacturing expert who consulted the six organisations on lean manufacturing practices. We believe using a single source (lean manufacturing expert) for soliciting data increases the judgmental consistency of the input data used in our study.

We review LMPs and the effects of LMPs on operational and environmental performance in the next section. Such a review facilitates the identification of gaps in the literature. Using rough set theory and TODIM method with three-parameter interval grey numbers in an iterative and integrative manner, a multi-criteria model to support investment decisions in LMPs is developed in Section 3. An illustrative example is provided. The findings and managerial implications are discussed in Section 4. The robustness of the model is evaluated through sensitivity analysis. In Section 5, we conclude with summary of findings, limitations of the study and areas for future research.

2. Background

2.1. *Lean manufacturing practices (LMPs)*

Lean manufacturing has its origins within the Toyota Production System where it was integrated with just-in-time practices in order to improve quality and delivery time (Krafcik 1988). LMPs may be clustered into distinct bundles of practices (McLachlin 1997). Lists of bundles of LMPs include just in time (JIT), total quality management (TQM), total preventive maintenance (TPM), human resource management, controlled processes, productive maintenance and involved employees.

Some of these bundles also reflect inter-organisational operations. This implies that organisations have extended adoption of LMPs through supply chain collaboration, with the ultimate goal of streamlining the broader life cycle of production processes (Chavez et al. 2015). As such, there have been some focus in the literature on developing supplier capabilities in efforts to improve performance (Bai and Sarkis 2010), engaging suppliers in planning and problem solving (Swink, Narasimhan, and Wang 2007) and in the design and development of products (De Toni and Nassimbeni 2000). Recent research has revealed the importance of downstream collaboration and involving customer participation (Martínez-Jurado and Moyano-Fuentes 2014). Successful implementation of LMPs needs both backward coordination with suppliers and forward coordination with customers along the supply chain to ensure that manufactured products are specifically designed, produced, packaged and delivered to meet operational and environmental objectives. Some of these objectives include ecological, natural environment and sustainability dimensions, seeking to achieve lean and green supply chain management performance (Dües, Tan, and Lim 2013).

In this paper, the LMPs classification developed by Panizzolo (1998) is used. This classification lists six different bundles including four internal LMPs and two external LMPs. The former include process and equipment, manufacturing, planning, and control, human resources and product design. Two external LMPs are supplier relationships and customer relationships. Using this initial classification, a summary of LMPs from the literature is shown in Table 1.

2.2. *Effects of lean manufacturing practices on operational and environmental performance*

Lean manufacturing literature suggests that the implementation of LMPs effect firms’ operational performance dimensions (Khanchanapong et al. 2014). However, some empirical research shows that LMPs are still inconsistent and ambiguously associated with environmental performance (Hajmohammad et al. 2013; Rao and Holt 2005).

Most empirical research supports the proposition that LMPs are positively associated with environmental performance. Hart (1995) argued that lean product design and process practices can critically influence environmental performance. Strong evidence was found that lean manufacturing, as measured by ISO 9000 adoption and low chemical inventories, is complementary to waste reduction and pollution reduction (King and Lenox 2001). Other researchers (e.g. Dües, Tan, and Lim 2013; Hajmohammad et al. 2013; Larson and Greenwood 2004) postulate that LMPs show similar positive effects on both operational and environmental performance. The continuous effort through LMPs to reduce operational waste either from discarded materials, consumption of energy or water usage typically means lower pollutant emissions, supporting

Table 1. A comprehensive listing and bundles of lean manufacturing practices.

Bundles	Lean manufacturing practices	Abbreviation
Supplier	Supplier involvement in design	S1
	Feedback to suppliers	S2
	JIT delivery by suppliers	S3
	Lean supplier development	S4
Production planning and control	Pull production / Takt time	S5
	Setup reduction	S6
	Smoothed (levelled) production	S7
	Total production maintenance	S8
	Visual management of production control (VPC)	S9
	Feedback of performance metrics (e.g. productivity, quality)	S10
	Statistical process control (SPC)	S11
	Root cause analysis for problem solving	S12
Process technology	Visual management of quality control (VQC)	S13
	Autonomation (Jidoka)	S14
	One-piece-flow (continuous flow)	S15
	Cellular manufacturing	S16
	Layout size and shape (LSS)	S17
	Concurrent engineering	S18
	Parts standardisation / modularisation	S19
	Design for manufacturability	S20
	Visibility and information exchange (VIS)	S21
Human resources	Team work and leadership (TWL)	S22
	Workforce involvement in solving problems	S23
	Multi-functionality and cross-training	S24
	Workforce autonomy / empowerment	S25
	Workforce recognition and reward	S26
	Continuous improvement (CI)	S27
	Workplace housekeeping (WHK)	S28
	Standardised work	S29
Customer	Customer involvement	S30

Sources: Bortolotti, Boscari, and Danese (2015); Sezen, Karakadilar, and Buyukozkan (2012); Saurin, Marodin, and Ribeiro (2011); Pettersen (2009); Shah and Ward (2007); Shah and Ward (2003); Cua, McKone, and Schroeder (2001); Panizzolo (1998).

improved environmental performance (Mackelprang and Nair 2010). It has been argued that LMPs lead to environmental efficiency due to the core principle of zero waste (Rothenberg, Pil, and Maxwell 2001).

There is evidence that some LMPs do not positively relate to environmental performance (Dües, Tan, and Lim 2013). These results suggest that firms may adopt LMPs that are valuable for improving operational results without being environmentally friendly. For example, Rothenberg, Pil, and Maxwell (2001) found that lean management and reduction of air emissions of volatile organic compounds (VOCs) are negatively associated. The potential conflict between lean principles and the objectives of environmentally friendly practices have been reported in Fahimnia, Sarkis, and Eshragh 2015. Thus, there is still not enough evidence of how and which LMPs affect environmental performance. Additional investigation of how LMPs may help organisations with environmental performance is needed to fill this gap. Utilising some form of normative, analytical tool to help organisations identify and select appropriate LMPs that can contribute to both operational and environmental performance can prove beneficial to practitioners.

2.3. *Evaluation and selection models for lean manufacturing practices*

MCDM models have been developed in the literature that aid strategic decision making in selecting LMPs by organisations to become leaner. Along this line, fuzzy logic based multi-preference, multi-criteria and multi-person decision making heuristics are used to select the value stream mapping tools for lean design (Vinodh, Thiagarajan, and Mulanjur 2014). Lean tool selection for manufacturing systems using the VIKOR method (Anvari, Zulkifli, and Arghish 2014) also fall into this realm of research. Use of the analytical hierarchy and network processes to structure the lean manufacturing related decision making problem is proposed by Vinodh, Shivraman, and Viswesh (2011). Single stage, individual models for evaluating and selecting various elements to enhance lean programs are increasingly being supplanted with multi-stage, multi-purpose methodologies. These more advanced tools are meant to overcome weaknesses of single stage individual approaches. For example, Wu, Xu, and Xu (2016) developed a multiple attribute group decision making (MAGDM) framework based on the 2-tuple linguistic computation model to evaluate the lean practices performance.

None of the above methods have been used for operational and environmental sustainability evaluation of LMPs. In this paper, we introduce a novel model that can be used to evaluate the operational and environmental performance of LMPs. Implementing LMPs can be resource intensive, with relative investments tending to be irreversible and having a long-term impact on the organisation's survival (Tiwari, Antony, and Montgomery 2008). Therefore, selecting an LMP should contribute to the maintenance and improvement of competitive advantage, but should also be associated with the convenience (ease) of implementation at the operational level. TODIM is a tool in solving MCDM problems while considering decision makers' psychological (perceptual) expectations of multiple attributes with discrete valuations.

To enhance the TODIM methodology, rough set theory and grey system theory will be combined to evaluate relative dominance degrees of a set of LMPs amongst each other. Such a combination will help to further reflect a decision maker's behavioural characteristics including reference dependence and loss aversion. In general, a crisp number is difficult for a decision maker to provide a precise evaluation regarding the most practical situations. To overcome this issue, a three-parameter interval grey number will be used to numerically model decision makers' subjective judgments within TODIM. Rough set theory complements the TODIM approach by identifying the LMP attribute importance (weight). This overcomes TODIM's need for additional information about variable weights.

3. An illustrative application

The methodological application in this paper considers the case of six manufacturing organisations $g = \{1, 2, \ldots, 6\}$, which have implemented LMPs at certain stages of their manufacturing and supply chain management processes. Two of these organisations are in aerospace, two in automotive, one in pharmaceutical and one in textiles. The in-action use period of LMPs in these organisations ranges from 4 to 12 years at the time of the study. All six organisations are recognised as being among the leaders in their sectors in terms of LMP implementation. Using a single LMP expert who participated in all six implementations and follow-ups as a consultant for soliciting data increased the consistency of the judgmental input data used in our study. The LMP expert was assisted by organisational decision makers in LMP projects in four cases and from two other consultant experts in the remaining two cases.

Step 1: Construct the original decision system.
The decision table (an information system) for investment evaluation of LMPs is defined first. The table is defined by $T = (U, C)$, where $U = \{S_i, i = 1, 2, \ldots, 30\}$ is a set of 30 LMPs. We assume there are four supplier related practices S1, … ,S4, eight production planning and control practices $S_5, \ldots, S_{12}$, nine process technology practices S13, … , S21, eight human resources practices S22, … , S29, and one customer related practice S_{30}. $C = \{c_j, j = 1, 2, \ldots, 15\}$ is a set of *15* sustainability attributes which includes organisational performance attributes and ease of implementation attributes.

In this study, environmental and operational performance are evaluated. Operational performance takes into account an organisations responsibilities for competitive priorities such as productivity enhancement (O1), quality improvement (O2), cost reduction (O3), delivery time shortening (O4) and safety (O5) (Anand and Kodali 2008; Ramesh and Kodali 2012). Environmental performance refers to the environmental impact of organisation's operations, including pollution discharge reduction (E1), green image improvement (E2), recycling of materials (E3), ISO 14001 certification (E4) and energy consumption reduction (E5) (Bai et al. 2012; Zhu and Sarkis 2004). The ease of implementation, on the other hand, refers to the level of difficulty associated with LMP implementation. There are five ease of implementation attributes (F1 to F5). These attributes include implementation cost (F1), implementation time (F2), top management commitment (F3), technical difficulty (F4) and relevant experience (F5) (Agarwal, Shankar, and Tiwari 2006; Hallgren and Olhager 2009).

Step 2: Determine the values of each LMP against all attributes.
In this step, each organisation or expert g is asked to evaluate each attribute j for each LMP i. The evaluations for organisational performance factors are initially textually described, ranging from 'Very Low (VL)' to 'Very High (VH)' or 'Not Applicable (N/A)'. The evaluations for ease of implementation factors are textual descriptions ranging from 'Very Hard (VH)' to 'Very Easy (VE)' and 'Not Applicable (N/A)'. As an example, the evaluation matrix of an organisational decision maker is presented in Table 2.

Step 3: Transform values into three-parameter interval grey numbers.
For treating vagueness and ambiguity in human evaluations, all textual values are transformed into three parameter interval grey numbers, which is shown in Table 3. A grey matrix s_{ij}^{g} from the initial textual matrix with expressions identified in this step are transformed into three-parameter interval grey values.

Table 2. The judgments for performance and ease degree of LMPs for one manufacturing organisation.

	Environmental Performance					Operational performance					Ease degree of implementation				
Lean manufacturing practices	*E*1	*E*2	*E*3	*E*4	*E*5	*O*1	*O*2	*O*3	*O*4	*O*5	*F*1	*F*2	*F*3	*F*4	*F*5
S1	L	VL	M	L	M	L	H	M	L	L	E	H	M	H	H
S2	H	M	M	M	H	M	H	M	H	H	VE	VE	E	E	E
S3	VL	L	N/A	VL	VL	VH	H	VH	VH	N/A	H	H	M	M	H
S4	H	M	H	M	M	H	H	H	H	L	VH	H	M	H	H
S5	L	L	L	N/A	H	H	H	VH	H	L	E	E	E	M	VH
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
S30	M	H	L	M	H	VL	H	H	VL	M	H	H	E	M	H

Table 3 Linguistic variables and their corresponding three-parameter interval grey numbers.

Performance linguistic variables	Ease linguistic variables	Three-parameter interval grey numbers
Not applicable (N/A)	Not applicable (N/A)	(0, 0, 0)
Very Low (VL)	Very Hard (VH)	(0, 0.1, 0.3)
Low (L)	Hard (H)	(0.1, 0.3, 0.5)
Medium (M)	Medium (M)	(0.3, 0.5, 0.7)
High (H)	Easy (E)	(0.5, 0.7, 0.9)
Very High (VH)	Very Easy (VE)	(0.7, 0.9, 1.0)

Step 4: Integrate three-parameter interval grey values of LMPs across decision makers and experts.
Given the six manufacturing organisations (g={1,2,3,4,5,6}), the integrated three-parameter interval grey values for LMP S_i attribute j, $\otimes S_{ij}$, can be calculated using expression (1):

$$\otimes s_{ij} = \frac{1}{G - NI}[\otimes s_{ij}^{1} + \otimes s_{ij}^{2} + \cdots + \otimes s_{ij}^{g}]\ \forall i, j \tag{1}$$

where $\otimes s_{ij}^{g}(i = 1, 2, \cdots m; j = 1, 2, \cdots n; g = 1, 2, \cdots G)$ is the attribute rating value of the g^{th} decision maker for LMP S_i, attribute j and can be described by three-parameter interval grey number $\otimes s_{ij}^{g} = (\underline{s}_{ij}^{g}, \tilde{s}_{ij}^{g}, \bar{s}_{ij}^{g})$. *NI* is the number of respondents who replied no implementation for an LMP S_i. Selected aggregated three-parameter interval grey attribute scores are presented in Table 4.

Step 5: Determine information content of each attribute.

Definition 1 Given lower approximation $\underline{R}X$ of a rough set, a grey lower approximation of X for attribute c with a three parameter interval grey number can be determined using expression (2):

$$X_i^c = \{S_k \in U | d_c(S_i, S_k) \le \delta\} \tag{2}$$

where δ is the inclusion threshold value and $0 \le \delta \le 0.5$. In our case, $\delta = 0.02$. That is, two LMPs S_i and S_k are members of the same set only if $d_c(S_i, S_k) \le \delta$ for $c \in C$, where $d_c(S_i, S_k)$ denotes the distance measure of two LMPs S_i and S_k for the value of attribute $c \in C$ from expression (3).

$$d_c(S_i, S_k) = \alpha\sqrt{(\underline{S}_{ic} - \underline{S}_{kc})^2} + \beta\sqrt{(\tilde{S}_{ic} - \tilde{S}_{kc})^2} + (1 - \alpha - \beta)\sqrt{(\bar{S}_{ic} - \bar{S}_{kc})^2} \tag{3}$$

where α, β are weight parameters, $0 \le \alpha \le 0.5; 0.5 \le \beta \le 1; \alpha + \beta \le 1$. The overall information content results for the attributes are summarised in Table 5.

Table 4. (selected) Aggregate three-parameter interval grey values of LMPs on all attributes ($\otimes s_{ij}$).

Lean manufacturing practices	Environmental performance				
	*E*1	*E*2	*E*3	*E*4	*E*5
S1	(0.4,0.6,0.78)	(0.38,0.55,0.73)	(0.4,0.6,0.8)	(0.38,0.53,0.63)	(0.35,0.55,0.73)
S2	(0.35,0.53,0.73)	(0.22,0.4,0.6)	(0.37,0.57,0.77)	(0.3,0.43,0.55)	(0.22,0.4,0.6)
S3	(0.18,0.37,0.57)	(0.07,0.23,0.43)	(0.28,0.45,0.62)	(0.02,0.08,0.18)	(0.1,0.27,0.47)
S4	(0.35,0.53,0.72)	(0.28,0.45,0.62)	(0.43,0.63,0.83)	(0.27,0.4,0.52)	(0.17,0.32,0.48)
S5	(0.13,0.3,0.5)	(0.08,0.25,0.45)	(0.25,0.45,0.65)	(0.08,0.13,0.18)	(0.35,0.55,0.75)
…	…	…	…	…	…
S30	(0.5,0.7,0.88)	(0.55,0.75,0.93)	(0.35,0.55,0.73)	(0.38,0.53,0.65)	(0.35,0.55,0.75)

Lean manufacturing practices	Operational performance					Ease of implementation				
	*O*1	*O*2	*O*3	*O*4	*O*5	*F*1	*F*2	*F*3	*F*4	*F*5
S1	(0.35,0.55,0.75)	(0.5,0.7,0.9)	(0.4,0.6,0.8)	(0.35,0.55,0.75)	(0.35,0.55,0.75)	(0.2,0.4,0.6)	(0.2,0.4,0.6)	(0.55,0.75,0.9)	(0.15,0.35,0.55)	(0.25,0.45,0.65)
S2	(0.33,0.53,0.73)	(0.5,0.7,0.9)	(0.37,0.57,0.77)	(0.43,0.63,0.83)	(0.18,0.35,0.52)	(0.47,0.67,0.85)	(0.47,0.67,0.85)	(0.5,0.7,0.87)	(0.43,0.63,0.83)	(0.47,0.67,0.85)
S3	(0.47,0.67,0.85)	(0.3,0.5,0.7)	(0.6,0.8,0.95)	(0.47,0.67,0.85)	(0.07,0.2,0.33)	(0.2,0.4,0.6)	(0.23,0.43,0.63)	(0.53,0.73,0.88)	(0.23,0.43,0.63)	(0.37,0.57,0.77)
S4	(0.4,0.6,0.8)	(0.53,0.73,0.9)	(0.43,0.63,0.83)	(0.5,0.7,0.9)	(0.18,0.35,0.52)	(0.15,0.33,0.53)	(0.15,0.33,0.53)	(0.48,0.67,0.82)	(0.17,0.37,0.57)	(0.28,0.47,0.67)
S5	(0.55,0.75,0.93)	(0.45,0.65,0.85)	(0.5,0.7,0.88)	(0.5,0.7,0.9)	(0.2,0.4,0.6)	(0.25,0.45,0.65)	(0.3,0.5,0.7)	(0.5,0.7,0.88)	(0.18,0.35,0.55)	(0.23,0.4,0.6)
…	…	…	…	…	…	…	…	…	…	…
S30	(0.23,0.4,0.6)	(0.5,0.7,0.9)	(0.3,0.5,0.7)	(0.28,0.45,0.65)	(0.35,0.55,0.75)	(0.15,0.35,0.55)	(0.15,0.35,0.55)	(0.65,0.85,0.98)	(0.2,0.4,0.6)	(0.4,0.6,0.78)

Table 5. Information content and relative weight for each attribute.

Category	Attributes	Information content	Relative weight
Environmental performance	$E1$	0.896	0.973
	$E2$	0.909	0.988
	$E3$	0.911	0.990
	$E4$	0.920	1.000
	$E5$	0.844	0.918
Lean performance	$O1$	0.887	0.964
	$O2$	0.840	0.913
	$O3$	0.898	0.976
	$O4$	0.873	0.949
	$O5$	0.900	0.978
Ease of implementation	$F1$	0.896	0.973
	$F2$	0.909	0.988
	$F3$	0.911	0.990
	$F4$	0.920	1.000
	$F5$	0.844	0.918

Step 6: Determine the relative weight of each attribute.
Expression (4) is used to identify the relative weight w_{jr} of attribute j. The calculated relative weights of all attributes are shown in Table 5.

$$w_{jr} = {}^{w_j}\!\big/_{w_r} \quad j, r \in 1, \ldots, n \tag{4}$$

where w_j is the weight of the attribute c_j,$w_r = \max\{w_j | j \in 1, \ldots, n\}$.

Step 7: Determine the overall dominance measures of each LMP.
The first sub-step involves partitioning a three-parameter interval grey matrix into three crisp matrices using expression (5).

$$[\otimes s_{ij}] = \begin{cases} [\underline{s}_{ij}] \\ [\tilde{s}_{ij}] \\ [\bar{s}_{ij}] \end{cases} \tag{5}$$

The second sub-step in this process is to determine the three values $\underline{\phi}_j(\underline{S}_i, \underline{S}_k)$, $\tilde{\phi}_j(\tilde{S}_i, \tilde{S}_k)$, $\bar{\phi}_j(\bar{S}_i, \bar{S}_k)$ of the dominance measures given in expression (6) for each of the crisp matrices. The attenuation factor θ of the losses is set to $\theta = 12$ which the range of values is $0 < \theta < \frac{\sum_{j=1}^{n} w_{jr}}{w_{jr}}$.

$$\phi_j(S_i, S_k) = \begin{cases} \sqrt{\dfrac{w_{jr}}{\sum_{j=1}^{n} w_{jr}}(s_{ij} - s_{kj})} & \mathit{if}\, s_{ij} - s_{kj} \geq 0 \\ \dfrac{-1}{\theta}\sqrt{\dfrac{\sum_{j=1}^{n} w_{jr}}{w_{jr}}(s_{kj} - s_{ij})} & \text{otherwise} \end{cases} \tag{6}$$

where θ is the attenuation factor of the losses. $s_{ij} - s_{kj}$ denotes the gain of alternative S_i over alternative S_k for attribute c_j if $s_{ij} - s_{kj} > 0$ and the loss of alternative S_i over alternative S_k for attribute c_j if $s_{ij} - s_{kj} < 0$.

The third sub-step uses expression (7) to determine the three values (the minimum possible value $\underline{\delta}(\underline{S}_i, \underline{S}_k)$, the most likely value $\tilde{\delta}(\tilde{S}_i, \tilde{S}_k)$, the maximum possible value $\bar{\delta}(\bar{S}_i, \bar{S}_k)$) of the overall LMP dominance measures for each attribute. The three overall dominance measures of LMPs for environmental performance attributes between LMPs S_i and

Table 6. Three global value of environmental performance attributes for LMPs.

Lean manufacturing practices	$\underline{\varepsilon}_i^E$	$\tilde{\varepsilon}_i^E$	$\bar{\varepsilon}_i^E$
S1	0.793	0.810	0.790
S2	0.567	0.594	0.615
S3	0.124	0.166	0.185
S4	0.588	0.592	0.579
S5	0.243	0.293	0.306
S6	0.177	0.149	0.119
S7	0.220	0.246	0.275
S8	0.517	0.555	0.579
S9	0.087	0.127	0.127
S10	0.408	0.467	0.505
S11	0.582	0.625	0.661
S12	0.754	0.774	0.794
S13	0.234	0.301	0.337
S14	0.663	0.669	0.666
S15	0.113	0.175	0.205
S16	0.044	0.040	0.000
S17	0.256	0.290	0.307
S18	1.000	1.000	1.000
S19	0.639	0.690	0.717
S20	0.963	0.969	0.991
S21	0.331	0.376	0.411
S22	0.747	0.768	0.797
S23	0.318	0.379	0.411
S24	0.184	0.220	0.252
S25	0.239	0.311	0.383
S26	0.312	0.400	0.448
S27	0.728	0.752	0.783
S28	0.000	0.000	0.000
S29	0.382	0.386	0.380
S30	0.843	0.861	0.862
Min	1.000	1.000	1.000
Max	0.000	0.000	0.000

$S_k \quad k \in m$.

$$\delta(S_i, S_k) = \sum_{j=1}^{n} \phi_j(S_i, S_k), \quad \forall(i,j) \tag{7}$$

Step 8: Determine the global value for each LMP.
The first sub-step is to determine the three values (the minimum possible value $\sum_{k=1}^{m} \underline{\delta}(\underline{S}_i, \underline{S}_k)$, the most likely value $\sum_{k=1}^{m} \tilde{\delta}(\tilde{S}_i, \tilde{S}_k)$, the maximum possible value $\sum_{k=1}^{m} \bar{\delta}(\bar{S}_i, \bar{S}_k)$) of the sum overall dominance measures for each category attributes between LMPs S_i and other $S_k \quad k \in m$.

The second sub-step is to determine the three global values $\underline{\varepsilon}_i$, $\tilde{\varepsilon}_i$, $\bar{\varepsilon}_i$ of the LMP S_i through normalisation of the corresponding overall dominance measurements for each category attributes using expression (8).

$$\varepsilon_i = \frac{\sum_{k=1}^{m} \delta(S_i, S_k) - \min_i \sum_{k=1}^{m} \delta(S_i, S_k)}{\max_i \sum_{k=1}^{m} \delta(S_i, S_k) - \min_i \sum_{k=1}^{m} \delta(S_i, S_k)} \quad i \in 1, \ldots, m \tag{8}$$

The global values and overall dominance measures of environmental performance attributes are given in Table 6.

Table 7. Final global value of LMPs for each category attributes.

Lean manufacturing practices	ε_i^E	Ranks on environmental performance	ε_i^O	Ranks on operational performance	ε_i^F	Ranks on ease of implementation
S1	0.801	4	0.413	19	0.299	25
S2	0.592	11	0.28	23	0.905	3
S3	0.16	26	0.354	21	0.439	17
S4	0.588	12	0.497	12	0.164	27
S5	0.284	22	0.632	9	0.363	22
S6	0.149	27	0.455	15	0.401	21
S7	0.247	23	0.395	20	0.56	13
S8	0.551	13	0.529	11	0.53	15
S9	0.117	28	0.031	28	0.728	6
S10	0.462	14	0.454	16	1	1
S11	0.623	10	0.483	13	0.727	7
S12	0.774	5	0.917	3	0.334	24
S13	0.293	20	0.097	27	0.877	4
S14	0.667	9	0.465	14	0.36	23
S15	0.167	25	0	30	0	30
S16	0.031	29	0.537	10	0.43	19
S17	0.285	21	0.42	18	0.06	29
S18	1	1	0.94	2	0.458	16
S19	0.684	8	0.884	4	0.535	14
S20	0.973	2	0.823	5	0.435	18
S21	0.374	17	0.317	22	0.799	5
S22	0.77	6	0.712	7	0.632	10
S23	0.372	18	0.443	17	0.574	12
S24	0.219	24	0.179	24	0.169	26
S25	0.311	19	0.11	26	0.08	28
S26	0.39	15	0.656	8	0.668	9
S27	0.754	7	1	1	0.626	11
S28	0	30	0.012	29	0.912	2
S29	0.383	16	0.749	6	0.701	8
S30	0.857	3	0.143	25	0.404	20

Step 9: Compute the final global value for each LMP.

ε_i is a final global value for an LMP S_i which is the highest ranked when considering the minimum possible value, the maximum possible value and the most likely value. Expression (9) is used to calculate the final global value of LMP S_i.

$$\varepsilon_i = \alpha\sqrt{(\underline{\varepsilon}_i - \min_i \underline{\varepsilon}_i)^2} + \beta\sqrt{(\tilde{\varepsilon}_i - \min_i \tilde{\varepsilon}_i)^2} + (1-\alpha-\beta)\sqrt{(\bar{\varepsilon}_i - \min_i \bar{\varepsilon}_i)^2} \tag{9}$$

The complete results for each category of attributes (environmental performance or operational performance or ease of implementation) are presented in Table 7.

4. Analysis of findings and sensitivity analysis

In this section, the results of the LMPs evaluation analysis are presented. Furthermore, using different parametric settings, a sensitivity analysis is provided. It should be noted that the findings reported are based on the input gathered from the six manufacturing companies studied. As such, although providing useful managerial insight, one should refrain from generalising the findings across industries and countries.

4.1. *Analysis of evaluation results*

An analysis of the LMPs rankings from five perspectives is now presented.

Operational LMPs: The top five important operational LMPs include: S_{27} (continuous improvement), S_{18} (concurrent engineering), S_{12} (root cause analysis for problem solving), S_{19} (parts standardisation / modularisation) and S_{20} (design for manufacturability) selected for this set of attributes are primarily the focused lean tools for improving the operational performance of the case organisations. In our study, S_{27} (continuous improvement) is identified to be of the highest importance and the most suitable practice to achieve good operational performance. According to the lean philosophy, an organisation should focus on removing all forms of waste and becoming truly lean in the long term. It can be argued that the attribute S_{27} not only is an LMP, but also is the mantra and philosophy of lean manufacturing (as also argued in Ramesh and Kodali (2012)).

Environmental LMPs: The top five ranked LMPs include: S_{18} (concurrent engineering), S_{20} (design for manufacturability), S_{30} (customer involvement), S_{01} (supplier involvement in design) and S_{12} (root cause analysis for problem solving) represent effective methods for improving the environmental performance within organisations. Comparatively, we observe that the LMPs that contribute to operational performance differ from those that contribute to environmental performance. It is interesting to note that continuous improvement, a bastion of operational management systems, is not viewed as a top LMP in improving environmental performance.

This finding shows that not all LMPs can simultaneously improve operational and environmental performance. This finding is consistent with previous research conclusions in that the effects of LMPs on environmental performance are still inconclusive and that 'win-win' may not always be possible (Rao and Holt 2005).

These findings can help organisations confirm and invest in those LMPs that have the highest potential to improve their performance. There are six common LMPs in the top 10 important operational and environmental LMPs, namely: S_{18} (concurrent engineering), S_{20} (design for manufacturability), S_{12} (root cause analysis for problem solving), S_{22} (team work and leadership), S_{27} (continuous improvement) and S_{19} (parts standardisation / modularisation).These LMPs would likely be the most successful for organisations seeking to be lean and green.

Ease of implementation LMPs: The LMPs that are easiest to implement include: S_{10} (feedback of performance metrics), S_{28} (workplace housekeeping), S_{02} (feedback to suppliers) S_{13} (visual management of quality control) and S_{21} (visibility and

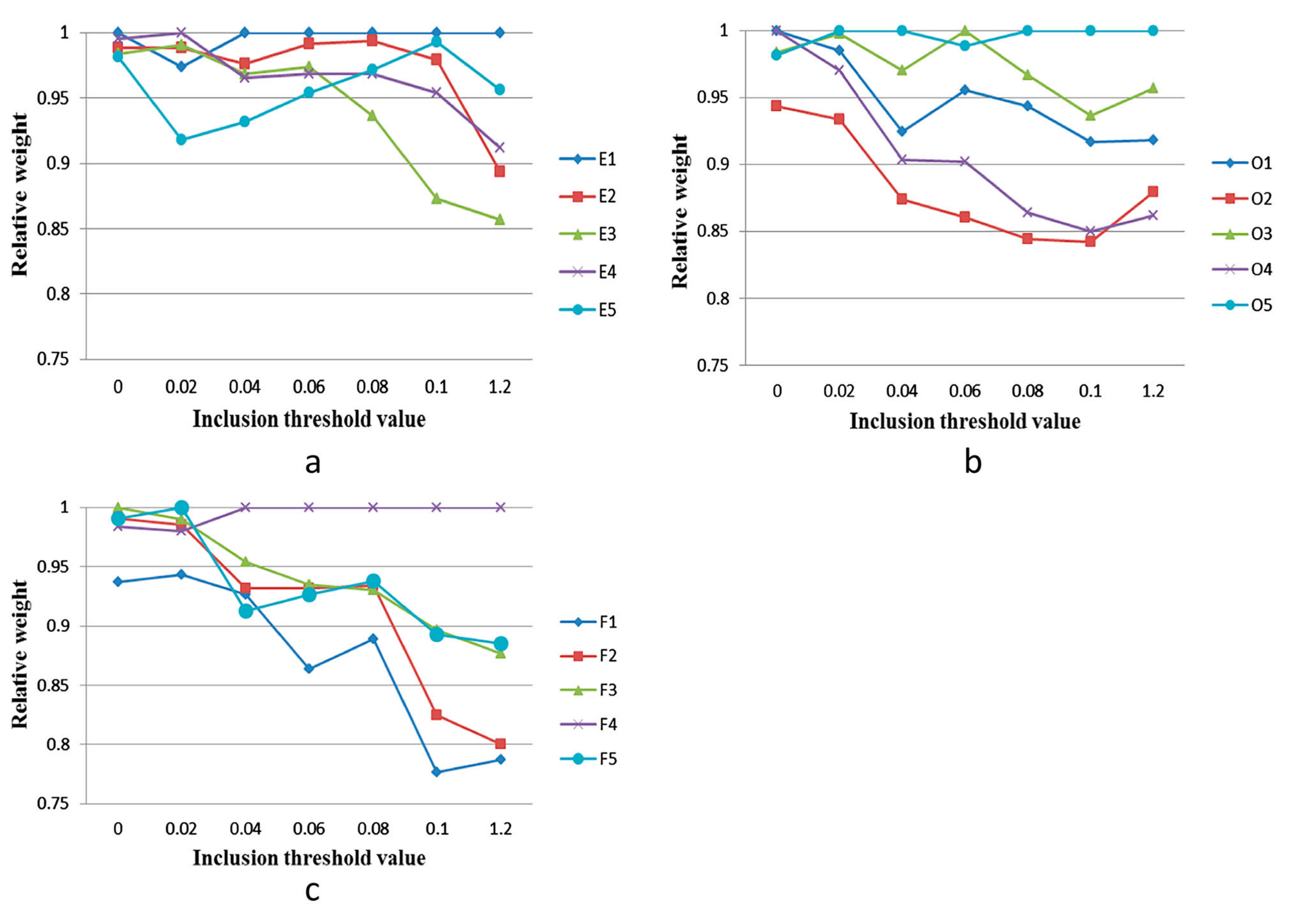

Figure 1. Weight of attributes for different δ values.

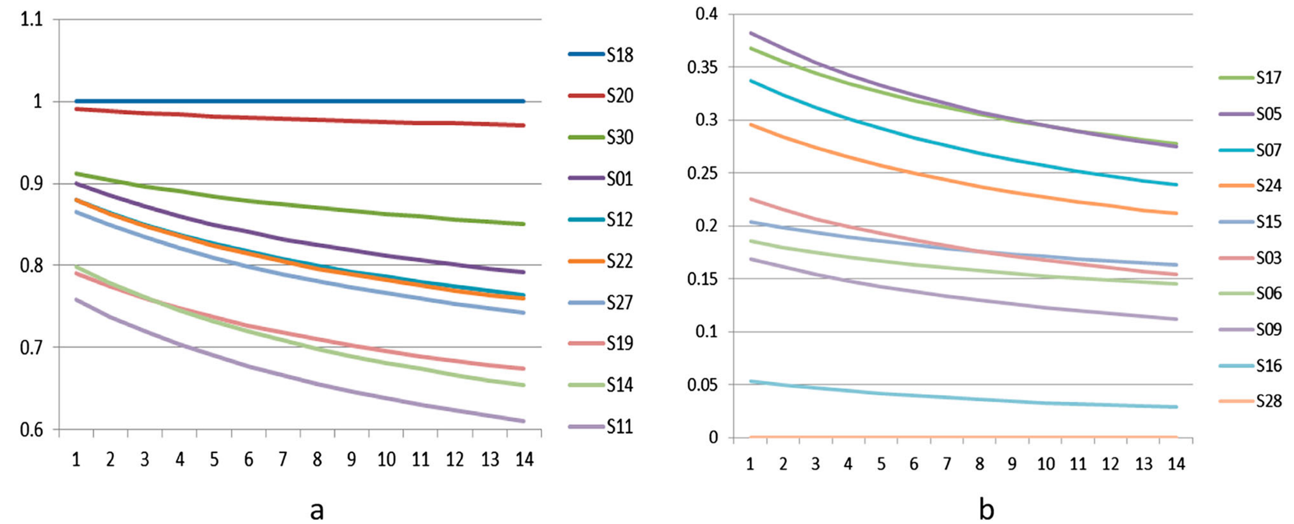

Figure 2. Final global value of LMPs for different θ values for environmental performance.

information exchange). The LMPs that contribute most to performance and those that are easy to implement differ significantly. Although there might be performance contributions from any one of the LMPs, the implementation of those that provide the greatest performance values may need to be put on hold due to their relative difficulty of implementation. Given that organisations, especially some small organisations, have limited resources and capacity, they may wish to start with easier to implement LMPs. Organisationally and politically, the easier to implement LMPs can be easy 'wins' that might pave the way for more difficult ones (with much higher performance improvement potential) to be eventually implemented.

Along with the above findings, two further general classifications are presented, namely 'Excellent LMPs' and 'Poor LMPs'.

Excellent LMPs: These LMPs represent overall good rankings in operational and environmental performance along with ease of implementation. To determine these LMPs, we consider the top 10 ranking LMPs across the performance attributes. Only one LMP S_{22} (team work and leadership) ranks in the top 10 for each classification. This LMP would likely be the easiest to implement while achieving simultaneous improvements in operational and environmental performance in making the organisation lean and green. As such, the organisations should further support team work and leadership as part of their operational practices. However, LMP S_{22} is still far from the best in terms of operational and environmental performance, and is ranked tenth in the 'ease of implementation' category. The top 10 LMPs in environmental performance average rank is 16.8 for ease of implementation. The top 10 LMPs in operational performance average rank is 15.1 for ease of implementation. Overall, it seems that the highly performing LMPs will encounter challenges in implementation. Thus, ease of implementation with potential benefits needs to be carefully evaluated and weighed by companies.

Poor LMPs: These LMPs result in inferior operational and environmental performance improvement potential coupled with difficulty of implementation. Two LMPs S_{15} (one-piece-flow) and S_{24} (multi-functionality and cross-training), which rank in the bottom 10 of each classification, fall into this category. Those LMPs are considered to lack both operational and environmental performance improvement potential and are difficult to implement. Organisations might consider to drop these LMPs from their implementation list, unless they can come up with ways to rectify the negatives.

4.2. *Sensitivity analysis*

The impact of the variations in the δ parameter (inclusion threshold) on the relative weight now analysed. The results are shown in Figure 1 for each performance criterion. When $\delta = 0$, the rough set model reduces to the basic rough set model and the equivalence relation will become very strict. If we were completing a rough set analysis at $\delta > 0.125$, then the near level of textual descriptions would be identical. Therefore, a more appropriate range for the inclusion threshold δ is [0.02, 0.12].

The results show that pollution discharge reduction (E1) was identified as the most important environmental performance attribute in most cases for $0.00 \leq \delta \leq 0.12$ as shown in Figure 1(a). Arguably, LMPs can contribute to reduce these environmental impacts because of their intrinsic focus on waste elimination (Azadegan et al. 2013). Safety promotion (C5) is identified as the consistently most important attribute for operational performance as shown in Figure 1(b), although it falls to second or third place for a couple δ values. It seems that these organisations have a strong focus on the safety of their workforce. They would like to achieve their business objectives without comprising safety standards (Ramesh and Kodali 2012). Technical difficulty (F4) was identified as the most important ease of implementation attribute as shown in Figure 1. A challenge for successful implementation of LMPs is that workers lack the capabilities to master LMPs (Taylor, Taylor, and McSweeney 2014), and more technically difficult LMPs face greater barriers in this respect. The difference of relative weights between any two attributes is not large, a 10% difference between any pair being the largest difference. Also, a relatively robust ranking of importance seems to exist.

We provide another analysis to determine the solution robustness when varying the value of θ, the attenuation factor for losses, for environmental performance. Figure 2(a) shows the top 10 LMPs based on environmental performance attributes. This result shows that for top ranked LMPs the ranking is relatively robust and the managers can be confident on these high performers. Figure 2(b) shows the bottom 10 LMPs based on the environmental performance attributes. Compared to base findings, the two changes in the ranking of the values occurred between S_{17} (layout size and shape) and S_5 (pull production / takt time) as well as, S_{15} (one-piece flow) and S_{03} (JIT delivery by suppliers). The ranking obtained was only slightly inconsistent and mostly for the lowest ranked LMPs. The results for $10 \leq \theta \leq 14$ are almost the same, pointing out the robustness of the methodology and the model developed.

5. Conclusion

5.1. *Summary of findings*

The implementation of LMPs could generate a competitive edge for an organisation. Yet, organisations want to become lean and green at a reasonable investment cost. Some organisations may lack experience in this respect, as well as the necessary tools and management skills. Thus, selection of and investment in LMPs require significant planning and management, especially with dual lean and green goals are aimed to be achieved simultaneously.

This study has proposed a grey based rough set and TODIM approach to support such LMP evaluation and investment decision in order to achieve environmental and operational goals. Operational performance and environmental performance attributes and the ease of implementation were used as attributes for LMP evaluation. The model was applied in a field study involving six manufacturing organisations. Rough set, TODIM and three-parameter interval grey numbers are complementary approaches that were methodologically integrated into the eight-step investment evaluation and appraisal process. A modified TODIM method was proposed based on the rough set and three-parameter interval grey numbers. A new measurement for rough set grey numbers was also introduced.

In practice, many outcomes of lean manufacturing practices are difficult to evaluate with practical data or crisp numbers. This has intensified the uncertainty associated with investing in LMPs. To evaluate LMPs, alternatives are scored in different criteria using three-parameter interval grey number. An outranking multi-criteria method with direct computation on three-parameter interval grey number is applied. The method deals with contextual variables, and enables a LMPs implementation planning and decision making.

In this paper, LMPs' impact on operational and environmental performance and ease of implementation were studied. An empirical study was conducted in six manufacturing organisations for ranking LMPs. The investigation illustrated those LMPs that were best or highly ranked for operational and environmental performance and ease of implementation. The analysis also showed which LMPs balance good performance and ease of implementation. These LMPs represent top priorities for investment and implementation. The sensitivity analysis conducted showed the robustness of the results.

Only one LMP, S_{22} (team work and leadership), ranked in the top 10 for each classification. Empirical evidence from the reviewed literature shows that an organisation cannot succeed in lean unless it has a strong leadership and skilled workers (Al-Najem, Dhakal, and Bennett 2012). Our study further confirms that top management commitment, leadership and teamwork are crucial in implementing a successful lean system.

Two LMPs S_{15} (one-piece-flow) and S_{24} (multi-functionality and cross-training) fall into poor LMPs which rank in the bottom 10 of each classification. If one-piece-flow is attempted, three problems arise for a manufacturer: variability, waste, and inflexibility (Brown, Collins, and McCombs 2006).These problems seriously damage the operational and environmental performance of the organisation. Multi-functionality and cross-training enable organisation-wide redesign of processes and practices, as well as, improve workforce agility. However, multi-functionality and cross-training can be time consuming and costly to implement. Implementation of this LMP is also constrained by worker learning capacity and can lead to ambiguity about work responsibilities and performance (Jordan, Inman, and Blumenfeld 2004).

5.2. *Limitations and future research*

The multi-stage model developed in this study provides useful insight and decision support for lean manufacturing management. However, like in any other study, our work also has its own limitations. Limitations of this study also reveal the areas for future research.

First, since the evaluation attributes were adapted from the three categories, some possible important attributes or categories may have not been considered. Future research should identify more attributes or categories to justify the implementation of LMPs, such as social sustainability dimensions. Second, the model used in this study did not consider all possible interactions between LMPs. Additional interactions between and within the LMPs could have been included. Another possible future research direction would be to use the analytic network process (ANP) or DEMATEL (Bai and Sarkis 2013) to incorporate inner and outer dependencies that occur among the LMPs. Findings can be compared with the basic findings identified here. Lastly, reporting of theoretical frameworks to guide organisations in making decisions on how to introduce and implement various LMPs is limited in the literature. A challenge for organisations is how to determine the LMP implementation sequence that leads to better environmental performance. A possible future research direction in this regard would be to use the NK method to develop a process model for introducing and implementing LMPs for organisations (Bai, Sarkis, and Dou 2017).

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Note

1. TOmada de Decisão Interativa e Multicritério – in Portuguese “Interactive and Multicriteria Decision Making”.

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