The Effect of Lean Methods and Tools on the Environmental Performance of Manufacturing Organisations

Abstract

Evidence suggests that lean methods and tools have helped manufacturing organisations to achieve operational excellence, and in this way meet both traditional and contemporary organisational objectives such as profitability, efficiency, responsiveness, quality, and customer satisfaction. However, the effect of these methods and tools on environmental performance is still unclear, as limited empirical research has been conducted in this field. This paper therefore investigates the impact of five essential lean methods, i.e. JIT, autonomation, kaizen/continuous improvement, total productive maintenance (TPM) and value stream mapping (VSM), on four commonly utilised measures for the compliance of environmental performance, i.e. material use, energy consumption, non-product output, and pollutant releases. A correlation analysis modelled the relationship and effect of these lean methods on the environmental performance of 250 manufacturing organisations around the world. Structural equation modelling (SEM) was used as a second pronged verification approach to ensure the validity of the results. The results indicate that TMP and JIT have the strongest significance on environmental performance, whereas kaizen/continuous improvement only showed an effect on the use of materials and release of pollutants. Autonomation and VSM did not show any impact on environmental performance. The research holds important implications for industrialists, who can develop a richer knowledge on the relationship between lean and green. This will help them formulate more effective strategies for their simultaneous or sequential implementation. The paper extends our knowledge in the lean and green field by helping us to establish and explain the given relationships between five of the most important and commonly used lean methods and the environmental performance of manufacturing organisations. No previous research had considered the studied lean methods and environmental measures of performance.

Keywords: autonomation; JIT; kaizen/continuous improvement; green lean; environmental performance; SEM; TPM; VSM.

1. Introduction

Lean manufacturing has been widely implemented by manufacturing organisations to achieve operational excellence, and in this way meet both traditional and contemporary organisational objectives such as profitability, efficiency, responsiveness, quality and customer satisfaction (Garza-Reyes, 2015a). Lean methods that enable the achievement of these objectives include just-in-time (JIT), total productive maintenance (TPM), autonomation, value stream mapping (VSM) and kaizen/continuous improvement (CI). Belekoukias et al. (2014) and Rocha-Lona et al. (2013) consider these as the most essential methods of the lean approach. Additionally, Shah and Ward (2003; 2007) recognise JIT, TPM, autonomation and kaizen/CI as lean practices that are frequently perceived in the scholarly literature as describing high performance lean manufacturers while Andreadis et al. (2017) and Womack (2006) contemplate VSM as one of the most significant lean methods.

JIT is based on producing the right goods at the right time (Womack and Jones 2003). This contributes in reducing space utilisation, inventory and wastes associated to the overproduction of goods. Commonly linked tools to JIT include pull systems, takt time, one piece flow, levelled production, cell manufacturing, visual control, kanban, JIT purchasing and multifunctional employees (Belekoukias et al., 2014; Rocha-Lona et al., 2014; Kumar, 2010). On the other hand, TPM helps to optimise predictive, preventive and corrective maintenance activities to achieve efficient and proficient production equipment (Konecny and Thun, 2011). TPM relies on tools such as single minute exchange of die (SMED), overall equipment effectiveness (OEE), planned maintenance, 5S, quality maintenance, autonomous maintenance, initial control before starting production, and a safety and hygiene environment (Rocha-Lona et al., 2013; Konecny and Thun, 2011). Furthermore, autonomation, also called jidoka, uses tools such as visual control systems (i.e. andons), a full working system and mistake proofing devices (i.e. poka-yokes) to reduce quality defects (Shingo, 1989). Additionally, VSM is a lean and visual-based method, which illustrates, identifies and measures waste that results from the incapability, inefficiencies and unreliability of money, machines, people, information, space, time, tools and material during a production process (Abdulmalek et al., 2007). This is supported by VSM tools that include flow diagrams and current and future state maps. Finally, CI, or kaizen, is one of the key processes in a lean organisation. The aim of kaizen is to remove waste through the incremental and continuous improvement of operations. Kaizen acts as a platform for the sustainment of lean once that it has been embedded as part of the culture of an organisation. Tools which are commonly associated to the kaizen strategy include 5S, continuous flow, run charts, 5whys, brainstorming, data check sheet, kanban, Pareto chart, Gantt chart, mistake proofing, process maps and VSM (Belekoukias et al., 2014; Rocha-Lona et al., 2013; Bhuiyan and Baghel, 2005).

Since its conception several decades ago, lean manufacturing has become the most influential paradigm in manufacturing (Forrester et al., 2010), with strong evidence suggesting it as an effective method to improve the competitiveness of organisations (Hines et al., 2004). However, the rise of concerns for the environment has forced manufacturing organisations to not only aim at achieving operational excellence but also to rethink how their operations and processes can become more environmentally sustainable. To this end, and despite some studies (e.g. Zhu et al., 2005), have suggested a relatively week relationship between green practices/performance and operational practices, where lean methods and tools can be considered part of, the study of the simultaneous, or sequential, deployment of lean manufacturing and green operations (hereinafter green) has emerged as a major part of the environmental improvement agenda (Cherrafi et al., 2017; Cherrafi et al. 2016; Garza-Reyes, 2015a; Garza-Reyes, 2015b). For example, Garza-Reyes (2015a) identified and defined, through a systematic literature review, six main research streams in the field of lean and green. These included (1) compatibility between lean and green, (2) their integration, (3) the integration of green lean with other approaches (e.g. six sigma, resilience, agile, etc.), (4) the proposal of measurement methods for green lean, (5) the impact of green lean on various measures of performance (e.g. financial, sustainability, operations, etc.), and (6) the application of green lean in various industrial sectors and organisational functions. Additionally, some limited research has been dedicated to investigate the impact of lean methods and tools on various measures of environmental performance, see Section 2. Nevertheless, the overall effect of lean methods and tools on environmental performance may still be considered inconclusive due to the nature of the research conducted. For instance, the research discussed in Section 2 has been mainly concentrated on very specific lean methods and tools; that is, it has not involved all those which nowadays are recognised as essential components of the lean approach (i.e. JIT, TPM, autonomation, VSM and kaizen/CI) (Belekoukias et al., 2014; Rocha-Lona et al., 2013). In the same way, the measures of environmental performance selected to investigate the effects of lean practices vary considerably from some researches to others.

Therefore, to complement and expand the limited body of knowledge on the effects that lean manufacturing has on the environmental performance of organisations, this paper investigates the impact of the main methods and tools of lean manufacturing (i.e. JIT, TPM, autonomation, VSM and kaizen/CI) on four commonly utilised measures for the compliance of environmental performance, i.e. material use, energy consumption, non-product output and pollutant releases (National Academy of Engineering, 1999; Ditz and Ranganathan, 1997). These environmental measures are also comparable to some of those employed by Zhu et al. (2008), i.e. reduction of air emission, waste water, solid waste and consumption for hazardous/harmful/toxic materials, to assess the effect of Green Supply Chain Management Practices on the environmental performance of Chinese manufacturers. Considering this, the research question addressed through this research is:

- *What is the effect of essential lean tools such as JIT, TPM, autonomation, VSM and kaizen/CI on the environmental performance of manufacturing organisations as measured by the use of material, energy consumption, non-product output and pollutant releases?*

The rest of the paper is structured as follows: Section 2 discusses previous works conducted in the field and highlights the gap in the academic literature that this investigation fills; Section 3 presents the research methodology followed to answer the formulated research question; the results of the correlations and structural equation modelling analyses are outlined in Section 4; whereas these are discussed in Section 5; finally, Section 6 provides the concluding remarks, limitations of the research and future research directions derived from it.

2. Lean manufacturing and its impact on environmental performance

Climate change, environmental degradation, and natural resources scarcity are some of the major challenges that humankind are currently facing. As major contributors to the conception of such challenges, manufacturing organisation have been forced to develop cleaner operations and production processes. One normal starting point for developing better strategies to support environmental sustainability is to explore the opportunities that currently used best practices, e.g. lean, may offer to tackle environmental challenges and how they can be adapted and implemented to meet sustainability requirements. In this context, various authors have conceptually discussed the effects that lean manufacturing methods and tools may have on the environment.

For instance, Vinodh et al. (2011) suggest that lean initiatives stimulate substantial environmental benefits and that, for this reason, companies ought to ponder the environmental impact and quantify sustainable gains associated with lean initiatives. Mollenkopf et al. (2010) advocate that lean companies are more likely to accept environmental innovations. Garza-Reyes (2015b) supports this argument by indicating that the lean's emphasis on waste reduction provides a better atmosphere to implement green initiatives to reduce environmental wastes such excessive consumption of water, energy or any natural resource. In addition, Garza-Reyes (2015b), Garza-Reyes et al. (2014) and Carvalho et al. (2011) mention that some of the waste reduction objectives of lean are 'naturally' aligned to good environmental practices. For example, unnecessary or excessive transportation of products and/or raw materials is one of the seven wastes tackled by lean manufacturing. In this case, when this waste is reduced/eliminated it does not only minimise operational costs but also the unnecessary consumption of natural resources (e.g. oil) and CO_2 emissions (Carvalho et al., 2011). This has been empirically shown by Garza-Reyes et al. (2016), who successfully adapted lean manufacturing principles and tools to improve the operational efficiency and environmental performance of the transport operations of a world leader logistics organisation in Mexico. On the other hand, excessive inventory is also considered a waste fiercely tackled by lean as it averts the rapid identification of problems, discourages communication and increases lead time (Hines and Rich, 1997). Inventory requires storage, lighting, and in some cases, it also needs to be heated or chilled, all of which have negative environmental implications (Franchetti et al., 2009). Thus, reducing or eliminating inventory as suggested by lean will not only benefit an organisation financially but also environmentally. All this indicates that lean can act as a catalyst for better environmental performance, facilitating companies the deployment of environmental practices and policies.

In contrast to the positive effects of lean on the environment argued by various authors, some contradicting arguments can also be found in the scholarly literature. For example, Cusumano (1994) argues that more frequents deliveries, as advocated by JIT, create traffic congestions and hence more CO_2 emissions. Lean also facilitates product variety through more rapid kanban and setup exchanges, as well as more frequent deliveries of smaller lots of components. This is positive from a marketing viewpoint as product variety generates higher demand for goods, the problem is that this crafts the need to dispose replaced products (Cusumano, 1994). This phenomenon may indicate that lean methods and tools may not always, or in all dimensions, have a positive effect on the performance of organisations, and/or that these need to be integrated with contemporary sustainability approaches, e.g. Circular Economy, to offset some of its negative effects on the environment. Finally, other aspects that may contribute to lean not having a positive effect on the environmental performance of organisations may be related to the divergences between lean and green initiatives argued in the scholarly literature. These include how waste is defined and customer expectations (Garza-Reyes, 2015b; Garza-Reyes et al., 2014).

Besides the conceptual discussions presented above regarding the potential effects of the implementation of lean methods and tools on environmental performance, a limited number of scholars have also focused on empirically investigating this phenomenon. For example, King and Lenox (2001) analysed 17,499 U.S. manufacturing establishments between 1991 and 1996, and found strong evidence that lean, as measured by ISO 9000 adoption and low chemical inventories, is complementary to waste reduction and pollution reduction. Hajmohamad et al. (2013) conducted a study in Canadian manufacturing plants to understand the roles of lean and supply management in regards to improving organisation's environmental performance. The result indicated that the know-how and skills gained when applying lean principles are favourable to the adoption of environmental practices and that those make such practices more effective. Chiarini (2014) studied the environmental impacts of VSM, 5S, cellular manufacturing, SMED and TPM on the production processes of five European companies. The results of the study showed that VSM can identify the environmental impacts of production processes, 5S improve waste management and reduces oil leakage, cellular manufacturing can decrease electricity consumption, whereas TPM can reduce oil leakages, and emissions of dusts and chemical fumes into the atmosphere. By contrast, no significant improvements in environmental impacts were observed from implementing SMED. Bandehnezhad et al. (2012) investigated the effect of lean practices in different functional areas of manufacturing firms on environmental performance. Based on a survey of 101 manufacturing organisation in Malaysia, they found that lean practices related to functional areas of process and equipment, human resource, product design and customer satisfaction have positive effects on environmental outcomes. Yang et al. (2011) explored the relationships between lean manufacturing practices, environmental management (e.g. environmental management practices and environmental performance) and business performance outcomes (e.g. market and financial performance). In general, the results of their study suggested that prior lean manufacturing experiences are positively related to environmental management practices. Rothenberg et al. (2001) examined the relationship between lean manufacturing practices and environmental performance, as measured in terms of air emissions and resource use, in 31 automobile assembly plants in North America and Japan. The results of the study indicate that lean and the reduction of air emissions of volatile organic compounds are associated negatively. Also, Rothenberg et al. (2001) found that lean practices contribute to the cleaning of solvents and paints, but it was also revealed that these are not sufficient to meet the most stringent air regulations. Evidence to support the link between lean and resources efficiency was also found. Finally, through empirical observations and a survey study Klassen (2000) observed links between investment in JIT and improved environmental performance.

Unlike these studies, this research investigates the effect of essential lean methods and tools such as JIT, TPM, autonomation, VSM and kaizen/CI on four commonly utilised measures for environmental compliance, i.e. material use, energy consumption, non-product output and pollutant releases. Thus, the aim of this study is not only to complement the previous research but also expand its reach and scope. In this way, this research fills a gap in the knowledge as current research in this field is still limited. Figure 1 illustrates the conceptual framework derived from the literature review and in which this study centres around. Therefore, the overriding hypothesis formulated and tested through this study is:

H: Essential lean methods and tools such as JIT, TPM, autonomation, VSM and kaizen/CI have a significant impact on the environmental performance of manufacturing organisations as measured by commonly employed indicators including material use, energy consumption, non-product output and pollutant releases.

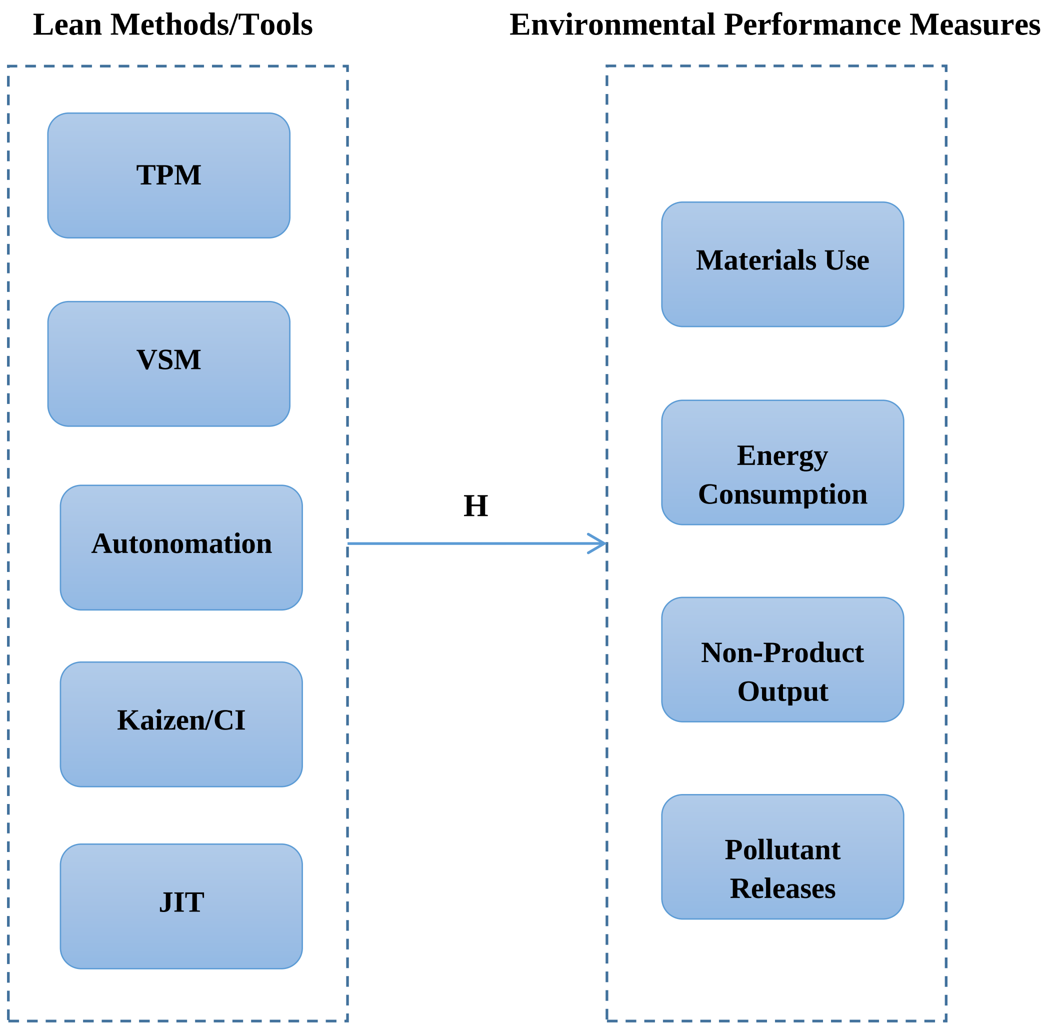


Figure 1. Conceptual Framework

3. Research methodology

To assess the effect of lean manufacturing on environmental performance, the association between the environmental measures of performance studied (i.e. dependent variable) was determined as an accrual of a number of explanatory independent variables (i.e. lean methods).

A survey questionnaire was designed using Qualtrics software to collect data for performing subsequent statistical analyses. The questionnaire consisted of 9 questions divided into two sections, see Table 1. Section 1 comprised a set of general profile and demographic questions, whereas Section 2 focused on investigating which of the lean tools, see Table 2, the respondent's organisations had implemented for every one of the lean methods studied. If a company had, for example, deployed five out of the nine JIT tools, then the extent of implementation of JIT was considered to be .555. This contributed in measuring the extent of deployment of every lean method. In addition, Section 2 of the questionnaire considered the perception of the respondents to investigate whether their companies had experienced any degree of improvement in the environmental measures of performance studied (i.e. material use, energy consumption, non-product output and pollutant releases) from the implementation of lean. For this, the respondents estimated the percentage of improvement achieved in every one of these environmental measures by using a Likert scale from 0 to 100%, with increments of 5% (i.e. 0, 5, 10, etc.).

<table>
<tr><th colspan="3">Table 1. Questionnaire overview and structure</th></tr>
<tr><th></th><th>Question</th><th>Reasons for Inclusions</th></tr>
<tr><td rowspan="3">Section 1</td><td>1. Select the size of your company</td><td rowspan="3">These questions were asked to understand the profile and demographics of the respondents.</td></tr>
<tr><td>2. Select the continent where you are supporting the operations of your company</td></tr>
<tr><td>3. Select the manufacturing sector where your company operates</td></tr>
<tr><td rowspan="6">Section 2</td><td>4. Which of the following lean manufacturing tools related to JIT has your company implemented? (see Table 2)</td><td rowspan="5">These questions investigated the degree of 'leanness' of the organisations that took part in the study. The results of these questions were correlated with question 9 to determine the effect of lean manufacturing methods and tools on environmental performance.</td></tr>
<tr><td>5. Which of the following lean manufacturing tools related to TPM has your company implemented?(see Table 2)</td></tr>
<tr><td>6. Which of the following lean manufacturing tools related to Autonomation has your company implemented? (see Table 2)</td></tr>
<tr><td>7. Which of the following lean manufacturing tools related to VSM has your company implemented? (see Table 2)</td></tr>
<tr><td>8. Which of the following lean manufacturing tools related to Kaizen/CI has your company implemented? (see Table 2)</td></tr>
<tr><td>9. Estimate the percentage of the improvement achieved in the following performance indicators due to the implementation of lean.
• Material use - quantities and types of materials used (Ditz and Ranganathan, 1997) - e.g. less material used per unit of product; less water consumption per unit of product; less packing material discharged per unit of product; less hazardous material used in the production process; increase water reused; increase processed, recycled or reused materials, etc.
• Energy consumption - quantities and types of energy used or generated (Ditz and Ranganathan, 1997) - e.g. less energy used per unit of product; less energy used per service or customer; increase in energy saved due to energy conservation, etc.
• Non-product output - quantities and types of waste created before recycling treatment, or disposal (Ditz and Ranganathan, 1997) - e.g. less waste per unit of product; less total waste for disposal, increase hazardous waste recycled; increase hazardous waste eliminated due to material substitution, etc.</td><td>This question intended to examine the level of improvement on environmental performance from implementing lean. This question was correlated with questions 4 to 8 to determine the effect of lean on environmental performance.</td></tr>
</table>

	• **Pollutant releases –** quantities and types of pollutants released to air, water and/or land (Ditz and Ranganathan, 1997) - e.g. *less specific emissions per unit of product; less wasted energy, less air emissions having ozone depletion and global climate potential, less material disposed to land fields, etc.*	

Table 2. Essential lean manufacturing methods and tools (adapted from Belekoukias et al., 2014 and Rocha-Lona et al. 2013)

	Lean Methods				
	JIT	**TPM**	**Autonomation**	**VSM**	**Kaizen/CI**
Lean Tools	One piece flow	OEE	Mistake proofing/Poka-yoke	Current state map	5S
	Pull system	SMED	Andon/visual control system	Future state map	Brainstorming
	Takt time	5S	Full work system	Flow diagrams	Continuous flows
	Levelled production	Autonomous maintenance			Kanbans
	Cellular manufacturing	Planned maintenance			Data checks
	Visual control	Quality maintenance			5whys
	Kanban/Pull production	Initial control before starting production			Pareto chart
	Multifunctional employees	Safety, hygiene and the environment			Run chart
	JIT purchasing				Gantt chart
					VSM
					Process map
					Mistake proofing/Poka-yoke

This study replicated the methodological approach followed by Belekoukias et al. (2014) for filling and distributing the questionnaire. Thus, the survey targeted operation related executives (e.g. Chief Operating Officers – COOs), operations/production/quality directors/managers, operations/process improvement managers/engineers and lean six sigma black belts who had knowledge on the subject and were familiar with the production processes of their organisations. According to Belekoukias et al. (2014), this type of respondents have both technical expertise on the subject matter and an accurate understanding of the company's performance before and after the deployment of lean. This also contributed in reducing the subjectivity of the study as these respondents had a deep and accurate understanding of their company's environmental performance before and after the lean implementation. In order to obtain less subjective and more uniform answers, the respondents were also briefed about various aspects of the questionnaire, including the Likert scale. Following the recommendations of Saunders et al. (2012) and Robson and McCartan (2016) to avoid/minimise any potential biased answers and protect the own personal privacy, interest and integrity of the respondents, the questionnaires were anonymous. Due to the complexity of adding an extra variable like 'time' to the analysis, the time taken by the surveyed organisations to sustain and/or reach the improvements achieved was not considered within the scope of the study. This 'extra-variable' can, however, be considered part of the future research agenda proposed from this study.

Besides the strategies employed to avoid biased answers, the questionnaire was validated, as suggested by Robson and McCartan (2016) and Groves et al. (1999), through a small-scale pilot study with experts. In this case, five experts from industry and academia where requested to check the questionnaire for reliability threats such as subject or participant error, subject or participant bias, observer error and observer bias (Robson and McCartan, 2016). Participant error and bias were further addressed by eliminating ambiguous and irrelevant questions (Binti Aminuddin et al., 2015). Experts also provided feedback on structural, presentation and linguistic aspects of the questionnaire and whether additional questions were needed to meet the objectives of the research. Observer error and bias were irrelevant to the questionnaire as fixed-alternative questions that did not require interpretation were used (Binti Aminuddin et al., 2015). Some questions were rectified and clarified further as a results of the pilot study.

Since this was an explanatory study, the questionnaires were distributed to respondents working in the manufacturing industry worldwide. The questionnaires were distributed via LinkedIn as a primary channel. In this line, 618 questionnaires were distributed directly through personal messages to lean experts (i.e. Chief Operating Officers – COOs), operations/production/quality directors/managers, operations/process improvement managers/engineers and lean six sigma black belts, along with a cover letter introducing the research and indicating its purpose. Additionally, the questionnaires were forwarded via e-mails to personal contacts of the authors. To broaden the pool of respondents, personal contacts were also requested to push forward the questionnaire to their own networks, producing in this way a 'snowballing sampling technique' (Horwitz et al., 2006). When initially contacted, the potential respondents were asked whether their organisations had implemented lean and whether they considered it as the main operations improvement strategy deployed by their companies. If the answer was positive to both of these questions, then the questionnaire was administrated to the respondent. Otherwise, the organisation was considered not suitable for the study. Out of the more than 618 questionnaires distributed, 250 responses were obtained. This sample size was considered acceptable, based on comparative studies in similar fields (e.g. Kirkham et al. 2014; Binti Aminuddin et al., 2015; Tachizawa and Gimenez, 2010; Kumar et al. 2014), to meet the objectives of this research and address the research question previously formulated.

To test the validity and reliability of the measurement scales used in this paper, firstly a Cronbach's Alpha test was conducted to test the reliability of the constructs. The test findings are shown in Table 3, which shows that all values are within the acceptable ranges (>=0.70). To test the constructs for convergent validity, the Average Variance Explained (AVE) factor was calculated. This AVE factor should be > 0.5 to ensure such validity of the constructs. Additionally, the Composite Reliability (CR) was also computed. In this case, to ensure the Composite Reliability of the constructs CR should be >.70. As indicated by Table 3, AVE values for all the constructs were >0.5 and CR values were > 0.70. This confirmed both the convergent validity and the composite reliability of the constructs under study. To test the discriminant validity of the constructs, Maximum Shared Variance (MSV) and Average Shared

Variance (ASV) were computed. For discriminant validity, MSV should be < AVE and ASV < AVE. As evidenced from Table 3, all the values were within the acceptable ranges, thus also confirming the discriminant validity of the constructs.

To test for the non-response bias, an independent t-test was conducted and compared with the early and late survey responses. The analysis showed that the t-test values were not significant, hence suggesting that there was not a significant difference between the early and late respondents. We also tested the data for common method bias. To do this, a Harman's single factor score test, shown in Table 4, was conducted. It showed that the data did not suffer from common methods bias issues as the variance explained by the single factor was <50% (no single variable accounted for more than 36% of the variance).

Table 3. Reliability, Convergent Validity and Discriminant Validity

Constructs	No. of Items	AVE	Composite Reliability (CR)	Cronbach's Alpha	MSV	ASV
VSM	3	0.69	0.74	0.71	.429	.280
Kaizen	12	0.55	0.86	0.82	.452	.362
Autonomation	3	0.59	0.74	0.70	.279	.233
TPM	8	0.53	0.79	0.74	.311	.246
JIT	9	0.54	0.79	0.81	.452	.332

AVE > .50; CR>.70; Cronbach's Alpha >.70; MSV < AVE; and ASV < AVE.

Table 4. Harman's single factor score test (Total Variance Explained)

	Initial Eigenvalues			Extraction Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.274	36.372	36.372	3.274	36.372	36.372
2	2.801	31.125	67.498			
3	.617	6.850	74.348			
4	.586	6.513	80.861			
5	.526	5.840	86.701			
6	.384	4.266	90.967			
7	.342	3.796	94.763			
8	.268	2.983	97.746			
9	.203	2.254	100.000			

Extraction Method: Principal Component Analysis.

The collected data was then subjected to a correlation analysis, which was performed using the IBM SPSS Statistics software version 23, to investigate the effect of lean methods on environmental performance. To verify the findings of the correlation analysis, a structural equation modelling (SEM) analysis was subsequently performed using the AMOS 22 software. SEM has emerged as a powerful statistical analysis technique that combines the factor analysis and multiple regression analysis, to analyse the structural relationship between measured variables (Kumar et al., 2011; Kumart et al., 2008; Shah and Goldstein, 2006; Koufteros, 1999). SEM has been previously used in similar lean studies, e.g. Belekoukias et al. (2014), to ensure the validity of regression and correlation analyses. Thus, the SEM analysis conducted in this study was considered of paramount importance to provide a strong validation for the previous statistical analysis carried out in this study.

4. Results

The findings presented in this section are based on the 250 valid responses obtained from the survey. The first section of the survey provided a profile and demographics' overview of the respondents and their organisations. In this line, over 73% of the respondents were employed by large organisations (i.e. >250 employees), whereas over 17% and 9% worked for medium side (i.e. between 50 and 250 employees) and small organisations (i.e. <50 employees) respectively.

In terms of their locations, 54.40% of the respondents' companies were operating in Europe, 20.40% in Asia, 20% in North America, 8.80% in South America, 4.40% in Africa, and 3.20% in Australia. Respondents were allowed to select more than one continent if their companies operated in various continental locations. The respondents' organisations competed in various manufacturing sectors such as transportation equipment (10.80%), primary metals (7.60%), machinery (7.20%), furniture and related products (2%), apparel (1.60%), printing and related support activities (1.20%), leather and allied products (.40%) and wood products (.40%). The rest of the organisations (68.80%) were classified as 'other', which included manufacturing sectors such as aeronautics, electronics, food, pharmaceutical, metal-mechanic, hydraulic components, among others. Although all of the 250 organisations that participated in the study had implemented all of the lean methods studied (i.e. JIT, TPM, automation, VSM and kaizen/CI), not all of them had implemented all of the lean tools shown in Table 2. With this, a level of application of the methods in the studied organisations was calculated as previously indicated in Section 3. In this context, VSM was the most extensively applied method with 74.93%, followed by kaizen/CI with 69.50%, TPM with 60.25%, JIT with 54.71% and autonomation with 50.67%.

Table 5 shows the results of the correlation analysis, i.e. correlation between the lean manufacturing methods JIT, TPM, autonomation, VSM and kaizen/CI, and the environmental performance measures studied, i.e. use of material, energy consumption, non-product output and pollutant releases.

Table 5. Correlation results

	Materials use	**Energy consumption**	**Non-product output**	**Pollutant releases**
Kaizen/CI	.198**	.095	.117	.163*
VSM	-.008	-.031	.053	.013
Autonomation	.069	.073	.051	.097
TPM	.254**	.226**	.253**	.227**
JIT	.225**	.177**	.218**	.209**

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

In terms of *material use*, the correlation analysis, see Table 5, showed a statistically significant relationship between JIT (0.254**), kaizen/CI (0.225**) and TPM (0.198**) with this measure of environmental performance at a 0.01 level (2-tailed) of significance. The analysis also indicated that material use is not affected by the autonomation and VSM lean methods. For *energy consumption*, the correlation analysis suggested that only TPM (0.226**) and JIT (0.177**) have a statistically significant effect on this measure of environmental performance at a significant level of 0.01 level (2-tailed), whereas kaizen, autonomation and VSM do not.

When focusing on *non-product output*, see Table 5, the correlation analysis showed that similar to energy consumption, this environmental performance measure is strongly and positively affected by the TPM (0.253**) and JIT (0.218**) methods at a 0.01 level (2-tailed) of significance. In this case, the rest of the lean methods studied (i.e. kaizen/CI, autonomation and VSM) do not have any major effect on non-product output according to the results of the correlation analysis. Finally, the correlation analysis indicated that in reference to *pollutant releases*, the TPM (0.227*) and JIT (0.209**) lean methods have a strong effect on this environmental measure of performance at a significant level of 0.01 level (2-tailed) while kaizen/CI (0.163*) presents the same level of impact but at 0.05 level (2-tailed) level of significance.

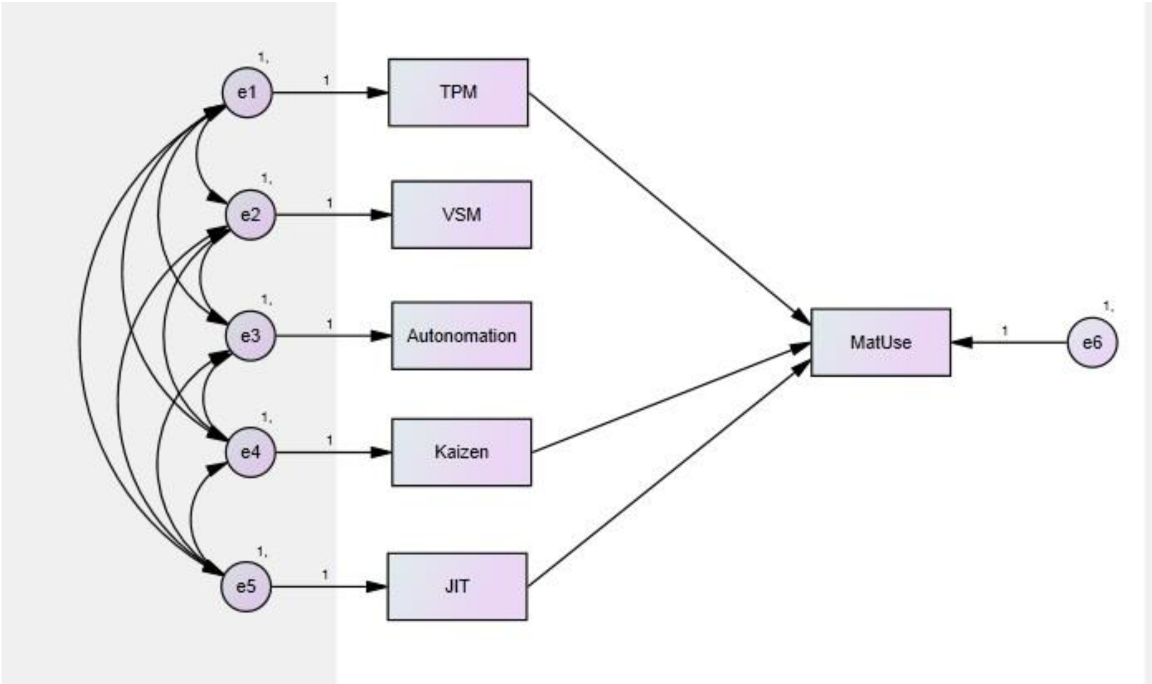
Table 6 illustrates and summarises the results of the correlation analysis and the strength of the impact of the lean methods studied on the four measures of environmental performance. For instance, Table 6 indicates that although all three TPM, JIT and kaizen/CI have a statistically significant impact on the use of materials, the strongest effect is that of TPM, followed JIT and kaizen/CI. For the same example, Table 6 also specifies that autonomation and VSM do not have any effect on materials use as the correlation analysis did not show any statistical significance between these variables. From Table 6, and the correlation analysis presented in Table 5, it is evident that TPM and JIT are the lean methods that have the strongest effect on environmental performance, followed by kaizen/CI. On the other hand, VSM and autonomation do not seem to have any impact on these environmental performance measures. Therefore, the result of the correlation analysis suggest that actions to improve the OEE of production equipment through the TPM method will have the strongest positive effect on the environmental performance of manufacturing organisations, followed by the implementation of a JIT delivery strategy, and the adoption of a kaizen/CI culture and use of its tools. In contrast, the results of this study, see Tables 5 and 6, indicate that no improvement in environmental performance will be achieved through the implementation/use of autonomation and VSM.

Table 6. Illustration and summary of correlation results

	Materials use	Energy consumption	Non-product output	Pollutant releases
Kaizen/CI	+	0	0	+
VSM	0	0	0	0
Autonomation	0	0	0	0
TPM	+++	+++	+++	+++
JIT	++	++	++	++

Notes: +++: strongest effect; ++: second strongest effect; +: third strongest effect – all of them statistically significant
0: Non-statistically significant effect

To cross verify the findings of the correlation analysis, the SEM technique was applied. The structural equation model focused on analysing the impact of each of the five lean methods studied on the four environmental performance measures. Therefore, four SEM models, see Figures 2(a), 2(b), 2(c) and 2(d), were constructed. The fitness indices of the best-fit model, for each environmental performance measure are shown in Table 7, which shows that all of them are within acceptable ranges. It is evident that the SEM models verify the correlation findings, for example, for material use, the best-fit model confirms a positive relationship with TPM, JIT and kaizen/CI and the absence of a significant relationship of this environmental measure with autonomation and VSM, see Figure 2(a). Thus, the SEM model corroborates the overall findings of the correlation analysis by showing that TPM and JIT affect all the four environmental performance measures, whereas kaizen/CI only have an impact on materials use and pollutant releases while VSM and autonomation do not show any impact on any of the performance measures.



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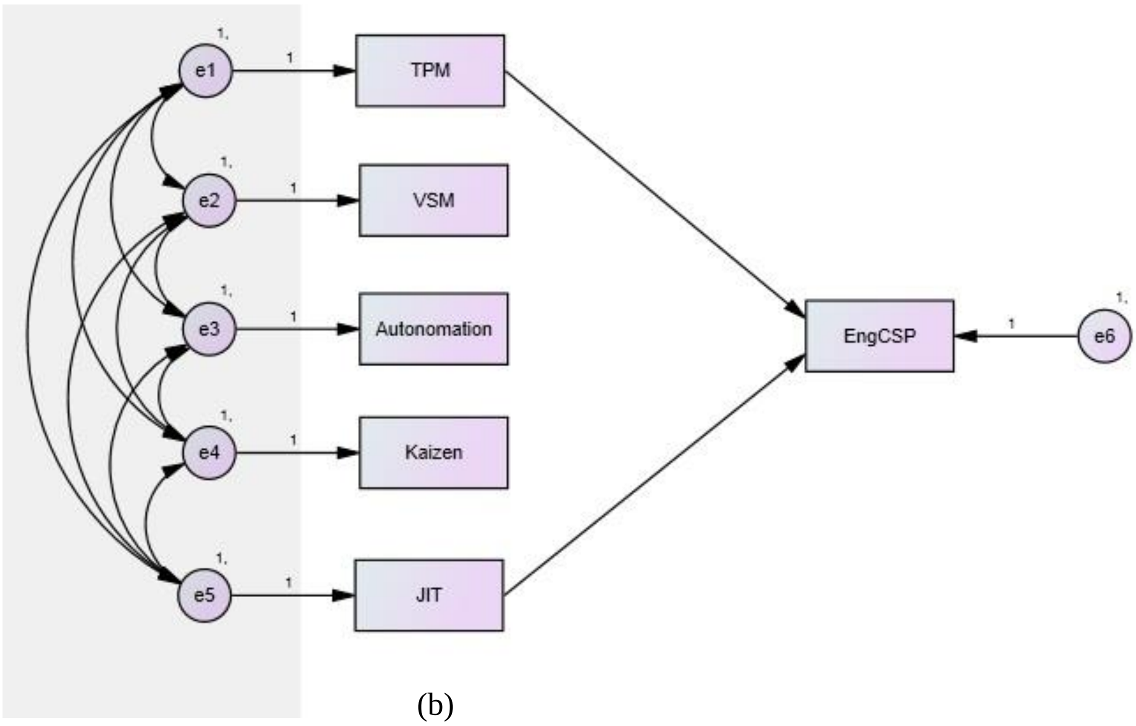
(a)



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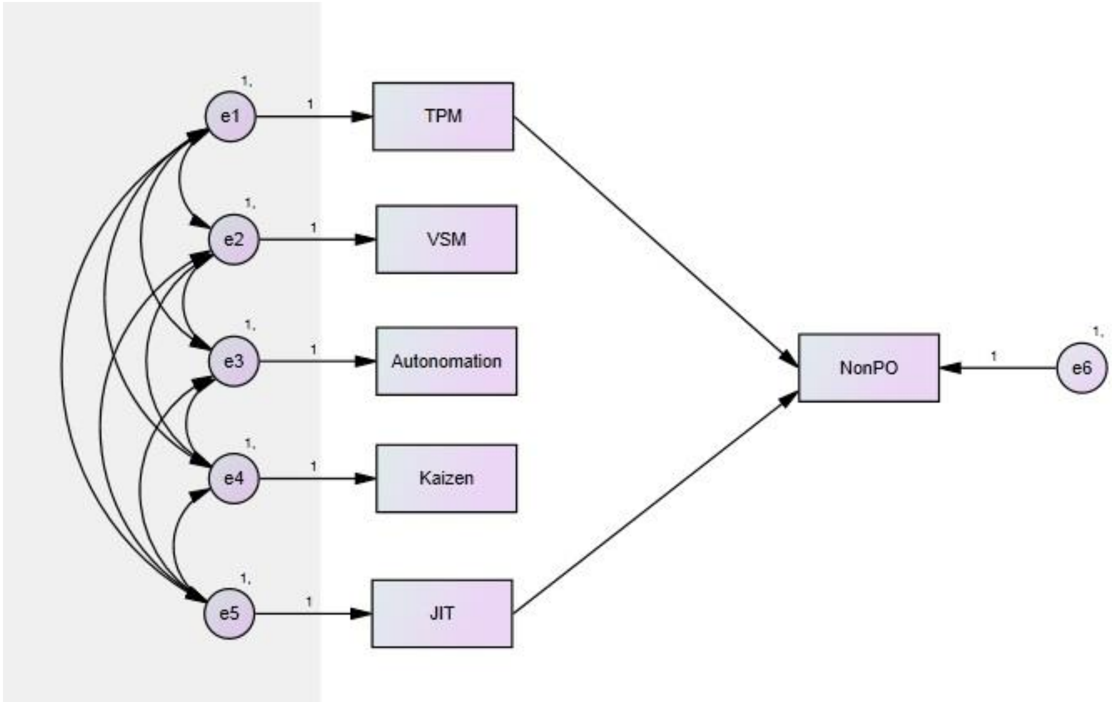
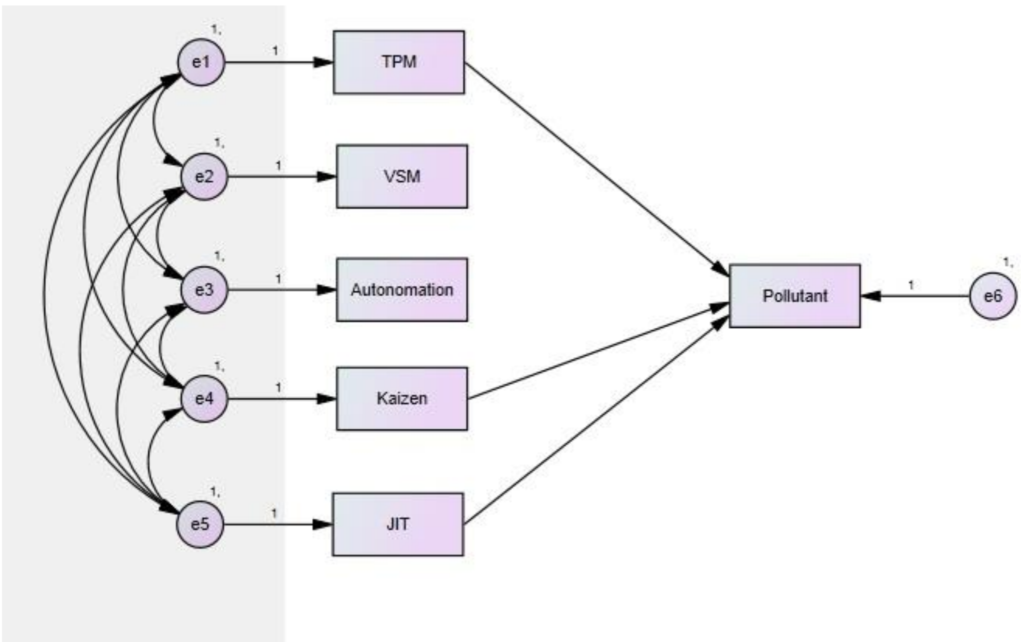


(c)



(d)

Figure 2. Best-fit model for (a) Material use, (b) Energy consumption, (c) Non-product output, and (d) Pollutant releases

Table 7. Fitness indices for best-fit path models

Best Fit Model/Fitness Indices	NFI (>.90)	RFI (>.90)	IFI (≈1)	CFI (≈1)	RMSEA	CMIN/DF
Non-product output	.994	.961	1.000	1.000	.005	1.007
Pollutant releases	.992	.921	.996	.996	.064	2.017
Materials use	.985	.845	.989	.989	.110	3.997
Energy Consumption	.987	.912	.993	.993	.070	2.231

5. Discussion of results

5.1 Material use measure

The correlation and SEM analyses suggested that TPM, JIT and kaizen/CI have a positive effect on the use of materials while autonomation and VSM do not, see Tables 5-7.

In the case of TPM, it intends to improve the performance and conditions of production equipment (Konecny and Thun, 2011). Thus, it is understandable to assume that TPM will have a positive effect on the use of material as production equipment that runs at an optimum condition will process raw material more efficiently and with less waste (Eti et al., 2004). Jasiulewicz-Kaczmarek (2014) comments that TPM provides a strict control on the functioning of production equipment, which reduces unplanned failures and human errors that in many cases result in raw material being wasted. Also, the material/resources used to run production equipment are reduced by TPM. For example, Chiarini (2014) empirically found that TPM helps to reduce oil leakages. Fliedner (2008) suggests that TPM’s 5S achieves a well-organised, cleaned, developed and sustained work place. Thus, this tool assists in a faster identification of spills and leaks, contributing in this way to the reduction of unnecessary material consumption. Furthermore, it can reduce materials and chemicals’ usage due to well-organised equipment, materials and parts. Keeping the floor clean to clearly expose any leak in a system is also one of the 5S characteristics that have a positive impact on reducing waste of material (Torielli et al., 2011).

The positive effect of JIT on the use of material was found to be the second most significant, see Table 6. It is well established in the academic literature that JIT has a significant and positive effect on quality by reducing inventory and consequently exposing problems (Belekoukias et al., 2014; Cua et al., 2006). Subsequently, it is also well established that quality reduces the consumption of material by eliminating/reducing scrap and rework (Shingo, 1989). This indicates that JIT can have a positive effect on the consumption of material through quality. In addition, as previously discussed, by reducing inventory, the use of other resources/materials needed to safely store inventory, e.g. electricity or gas, can be reduced (Franchetti et al., 2009). Garza-Reyes et al. (2016) also suggest that by following the JIT's advice of having smaller deliveries, smaller vehicles can be utilised, resulting in less fuel consumption.

In the case of kaizen, the results obtained from this study are in line with what it has been strongly stated in the academic literature regarding the positive effects of this lean method on the use of material. Farish (2009) comments that Toyota has actively adopted kaizen to minimize environmental effects like disposals to landfill, use of energy and water. Additionally, Vais et al. (2006) empirically demonstrated that the implementation of lean techniques such as 5S, kaizen and autonomous maintenance can enhance environmental performance by optimising ecological resources consumption and production output. Other authors such as Pampanelli et al. (2011) and Ross and Associates (2000) have also suggested that kaizen/CI can be used to enhance sustainability, especially through the reduction of material consumption. Therefore, the positive effect of TPM, JIT and kaizen/CI on material use found in this study seems to be aligned to these conceptual and empirical evidence presented.

In contrast, the correlation and SEM analyses did not only indicate a non-effect of autonomation and VSM on the use of material but also on all the other measures of environmental performance, i.e. energy consumption, non-product output and pollutant releases. Autonomation's main objective is to improve quality by preventing quality defects

(Shingo, 1989). Following the same reasoning for JIT regarding the positive effect of quality on the use of material, a positive effect of autonomation on this measure would have been expected. However, the results of this study contradict this reasoning, and the notion that some autonomation tools such as visual control systems can contribute in reducing material consumption and improving sustainability (Bandehnezhad et al., 2012; Vinodh et al., 2011). However, Biggs (2009) considers that visual control tends to have more side-effects on environmental performance than direct interventions. This may be one of the reasons as to why this study did not find a positive effect of this lean method on material use, or any of the other measures of environmental performance, see Tables 5-7. To have an effect on environmental performance, Tice et al. (2005) suggest that standard work and visual controls should be integrated with energy management systems (EMS) responsibilities and processes.

In the case of VSM, Abdulmalek et al. (2007) state that its main objective is to identify waste in manufacturing systems. The current state VSM identifies value-added and non-value added activities in transformational processes. Since some environmental wastes are embedded in the seven lean wastes (Garza-Reyes, 2015a; Garza-Reyes et al., 2014; Carvalho et al., 2011), it can be implied that identifying wastes in a manufacturing system through a VSM can have a positive impact on environmental performance. Fliedner (2008) agrees that VSM magnifies the benefits of environmental performance through less scrap and energy consumption. Chiarini (2014) found that VSM can be applied to investigate the environmental effects of manufacturing processes. Kurdve et al. (2011) successfully adapted the traditional VSM into an environmental-VSM to focus, particularly, on identifying environmental wastes. However, the results of this study contradict these notions but support those from Venkat and Wakeland (2006) and Brown et al. (2014), who suggest various limitations of this lean method when used for the improvement of environmental performance. Based on the practical and research experience of the authors, we are convinced of the potential value and effectiveness of kaizen/CI, autonomation and VSM to not only reduce material consumption but also reduce energy consumption, non-product output and pollutant releases. Since the results of this study contradict some of the literature and our experience, further studies in relation to the effect of these lean methods on environmental performance are suggested as part of the future research agenda.

5.2 Energy consumption

TPM was found to have the strongest effect on the reduction of energy consumption, followed by JIT, see Table 6. Equipment operating at an optimum condition will be more efficient and hence will consume less energy (Eti et al., 2004). Also, TPM can reduce non-value adding energy use from lighting, heating and cooling during a machine's standby as well as reducing the non-value adding energy which in some cases is needed to re-start some equipment after a breakdown. In an empirical study, Chiarini (2014) found that TPM helps to turn off the use of energy in a cell and in equipment in general, which lowers non-value adding standby energy use. Thorough the same study, Chiarini (2014) also found that the TPM's tool SMED contributed in reducing electricity consumption in some manufacturing equipment, although this was not significant. Torielli et al. (2011) suggest that the TPM's tool 5S can promote energy efficiency by taking care of the machines and items' standard operating procedures as well as developing indicators to show the correct status of a system. In the case of JIT, since it reduces inventory's volume (Shingo, 1989), it can help to reduce the energy required to safely store it (Franchetti et al., 2009). In addition, Chiarini (2014) found that by grouping machines, staff and workplaces dedicated to similar products in a single cell (i.e. JIT's cellular manufacturing) the transportation of material is greatly reduced, resulting in a significant reduction of energy consumption of electric trucks used to move material within a factory. In summary, all this evidence suggests that both TPM and JIT can have a positive effect on the reduction of energy in manufacturing environments. This is aligned to the results obtained in this study.

In reference to kaizen/CI, autonomation and VSM, the results of the correlation and SEM analyses on energy consumption are the same as for that of materials use, except for kaizen/CI, which showed some moderate effect on material use. The possible reasons for these three lean methods not having an effect on energy consumption, see Tables 5-7, may be similar to those highlighted in the aforementioned discussion in the material use section.

5.3 Non-product output

Similarly as in the case of energy consumption, TPM and JIT were found to have a positive effect on non-product output while kaizen/CI, autonomation and VSM were not, see Tables 5-7. Fliedner (2008) comments that TPM is primarily responsible for enhancing the reliability and durability of equipment and, at the same time, reducing spillages and leakages. This results in the reduction of solid and hazardous waste (Fliedner, 2008). Eti et al. (2004) also mention that equipment failures can adversely affect the quality of the end-product, not only contributing in this way to wasting materials, see Section 5.1, but also producing scrap. These views are in line with the results obtained from this study. However, TPM may still have some adverse environmental effects in this category as King and Lenox (2001) argue that the TPM's tool SMED increases the number of cleaning products, which leads to raising disposal of unwanted materials. This, however, is not reflected through the results of this study. In the case of JIT, a case study carried out by Ross and Associates (2004) revealed that JIT can reduce the disposal of out-of-date products that result from excessive inventory and the introduction of new product versions or lack of demand. Additionally, Fliedner (2008) suggests that the JIT's pull system can cut down inventory during and post process, reducing in this way the damage and deterioration of products and hence improving green performance.

Although the nature of kaizen/CI, autonomation and VSM may suggest that all of these lean methods would contribute in reducing non-product output through the identification and elimination of waste as well as the improvement of quality and efficiency (Abdulmalek et al., 2007; Bhuiyan and Baghel, 2005; Shingo, 1989), their effective implementation, management and sustainment may also play a critical role in their contribution to enhance environmental performance. This may have acted as a barrier for the studied organisations to experience the theoretical environmental benefits that these approaches may contribute with.

5.4 Pollutant releases

Pollutant releases have been widely used as a measure of green performance (King and Lenox, 2001). In this case, the study found that TPM, JIT and kaizen/CI have a positive effect on pollutant releases, whereas autonomation and VSM do not, see Tables 5-7. Through an empirical investigation, Chiriani (2014) found that TPM strongly contributed in reducing dusts and fumes in five manufacturing organisations. This came as a result of a more effective maintenance of the filters, piping and chimney of production equipment (Chiriani, 2014). Torielli et al. (2011) comment that the TPM's 5S tool pays attention to uncontrolled waste or emissions due to the fact that they do not fit within the standard. Despite the lack of further research on the effect of maintenance, and TPM, on environmental performance, and specifically on pollutant releases, it is not difficult to assume that well maintained production equipment will operate at an optimum level, reducing the emissions of harmful gases to the atmosphere, including CO_2. In the case of JIT, there seems to be some contraction regarding its effect on the reduction of pollutant releases. For instance, Venkat and Wakeland (2006) comment that delivering smaller batches increases the frequency of transportation, which generates a greater amount of CO_2 emissions. Also, using larger batches, for example, when painting cars with the same colour can diminish the emissions of air pollutant, but this approach contradicts the JIT's principle (Rothenberg et al., 2001). In this case, the results of this study contradict these views, but support that of Sarkis (2001), who suggests that JIT may reduce transportation time and hence emissions. The results also contradict the notion that VSM does not contribute to reduce pollutant releases as Garza-Reyes et al. (2016) and Simons and Mason (2003) have successfully used this approach to this end. This, and the fact that autonomation may not have been shown any effect on pollutant releases, and on any other environmental measure, may be the result of the lack of an effective implementation, management and sustainment of these methods as previously discussed.

6. Concluding remarks, limitations and future research directions

This paper investigates the relationship and impact that some of the most essential lean methods (i.e. JIT, TPM, autonomation, VSM and kaizen/CI) have on four commonly utilised measures for the compliance of environmental performance (i.e. material use, energy consumption, non-product output and pollutant releases). The study uses a two pronged verification approach by using the correlation and SEM methods to ensure the validity of the results. Therefore, this study fills a research gap as previously established in Sections 1 and 2, and extends our knowledge in the lean and green field by:

- Exploring and helping us to better understand the effect that the implementation of lean manufacturing has on the environmental performance of manufacturing organisations;
- Defining the degree of strength of the effect of the lean methods JIT, TPM, autonomation, VSM and kaizen/CI on the use of material, consumption of energy, production of non-product output, and release of pollutants. No previous studies had considered all the same lean methods and environmental measures of performance investigated in this study; and
- Explaining the given relationships and effects.

These contributions are beneficial for manufacturing managers who aim to gain a better understanding of the relationship and effect that some of the most essential lean methods have on the environmental performance of their operations. Therefore, our study provides a good insight of these relationships that can assist managers to take better decisions and formulate more effective strategies for the simultaneous, or sequential, implementation of lean, and environmental practices. This will help them to aim at not only improving profitability, efficiency, responsiveness, quality, and customer satisfaction, but also comply with environmental regulations and contribute to tackle some of the major challenges currently faced by humankind such as climate change, environmental degradation, and natural resources scarcity. Due to the need of organisations in other sectors, besides manufacturing, such as logistics and transport, healthcare, services, among others, to achieve these objectives, and the wider applicability of lean and green, other industries can also benefit from this study. Like the manufacturing industry, all these sectors are under intense pressure to operate competitively while at the same time making sure that their operations meet the environmental sustainability needs of the wider society. The effective implementation of green lean can provide them with an opportunity to achieve this endeavour.

Overall, the paper provides some interesting insight into the effects of lean manufacturing on environmental performance. This may encourage organisations not currently embarked or fully committed to sustainability to contemplate the business benefits that green lean may bring to their operations. Therefore, the paper provides trustworthy evidence for practitioners of the relationship between lean and environmental performance and can guide them to prioritise the deployment of lean methods based on the environmental performance measures they consider more strategically important to improve.

Various constraint factors which limited the extent and scope of the research, and its results, were encountered. These are important to be highlighted in order for future studies to consider them and to define the agenda for future research. Firstly, the study was carried out within the boundaries of the manufacturing sector only. Thus, further research is needed to provide added insights of the effect of lean manufacturing, and it methods, on the environmental performance of organisations operating in other industrial sectors. This will shed further light on the role that industry characteristics may have on the effect of lean manufacturing impact on environmental performance. Secondly, the study excluded academic experts as it was only focused on industrial experts. In future research, similar work can also be underpinned by academic and research experts in the field and not only by pragmatic sources. Thirdly, due to the strategy and structure followed in this paper to collect data, this study also suffers from the fact that the Likert-style rating scale for the survey limits the ability of respondents to express opinions other than the pre-set answers. To overcome this limitation, future research can be coupled with qualitative interviews with selected companies. This will also contribute in validating the results further. Finally, in this research, the effect of lean methods was investigated in reference to one of the pillars of sustainability, i.e. environment. Plenty of research has also been carried out in relation to the effect of lean on the profit pillar of sustainability. However, very limited research has investigated the effect of lean implementation on the societal dimension of sustainability. This is part of the future research agenda derived from this research and we encourage researchers to take steps in this direction.

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