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Lean and green combine to impact environmental and operational performance

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We assess the antecedent link between lean and green practices and assess the combined impact of lean and green practices on both environmental and operational performance. A lean and green practices performance model is proposed that incorporates lean and green practices as antecedents to both environmental and operational performance. Structural equation modelling was used to analyse data collected from a sample of 182 manufacturing managers in U.S. plants. We found that lean manufacturing practices are positively associated with environmental performance and operational performance and that green supply chain management practices are positively associated with environmental performance and environmental performance is positively associated with operational performance. No support was found for the idea that green supply chain management practices are positively associated with operational performance. While lean practices were found to directly affect environmental performance, the indirect effect of lean practices on environmental performance through green practices is stronger, indicating complementarity.

Keywords: advanced manufacturing processes; environmentally friendly manufacturing; lean manufacturing; green manufacturing; structural equation modelling; sustainable manufacturing; complementarity

1. Introduction

Manufacturing organisations have begun to adopt environmentally sustainable practices in response to increasing demand from customers for eco-friendly products and services (Green, Toms, and Clark 2015). The positive association between environmental sustainability strategy and environmental and organisational performance is well established in the literature (Green et al. 2012). Yet, an extensive literature review suggests that lean and green practices may not always be compatible (Mollenkopf et al. 2010).

Considering that customers demand environmental sustainability and that environmental sustainability leads to improved organisational performance, it is now important to identify necessary antecedents to the successful implementation of environmental sustainability practices. Since lean manufacturing practices aim to eliminate all forms of waste (Pavnaskar, Gershenson, and Jambekar 2013) and green supply chain management practices aim to specifically eliminate environmental wastes (Zhu, Sarkis, and Lai 2008; Green et al. 2012), it is logical to argue that having lean practices in place will support the successful implementation of green supply chain management practices. We propose that firms that have successfully implemented lean practices are better able to successfully implement the more environmentally focused green practices.

It is our purpose to fill a gap in the literature identified by Hallam and Contreras (2016) by providing an empirical integrated operating model of the firm relating lean and green. We assess the antecedent link between lean and green practices and assess the combined impact of lean and green practices on both environmental and operational performance. A lean and green practices performance model is proposed that incorporates lean and green practices as antecedents to both environmental and operational performance. To facilitate assessment of the model, data collected from a sample of 182 manufacturing managers working in U.S. manufacturing plants are analysed using a structural equation modelling methodology.

The literature associated with lean and green practices and the impact of those practices on environmental and operational performance is briefly summarised in the justification of the study with more detail appearing later with the support for the model and hypotheses. Subsequent sections include a description of the methodology employed to answer the research question, a presentation and interpretation of the statistical results related to assessment or the validity and

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reliability of the measurement scales employed and the assessment of the structural model. Finally, conclusions are developed and discussed.

2. Theoretical background

Complementarity Theory (Milgrom and Roberts 1990; Bergmiller and McCright 2009; Narasimhan, Swink, and Viswanathan 2010) serves as the theoretical underpinning of this study. Lean manufacturing practices and green supply chain management practices are organisational competencies or resources that result in competitive advantage when adopted by manufacturing firms. Lean practices and green practices are not easily implemented, requiring strategic focus, culture modification and significant investment. Lean practices and green practices are complementary in that the implementation of one set of practices supports the implementation of the other set of practices and this combination of practices leads to a levels of improved environmental and operational performance that could not be achieved through the implementation of either set of practices alone.

Fundamentally, lean manufacturing practices related to suppliers, customers, setup times, pull systems, preventive maintenance, employee involvement, statistical process control and continuous flow are designed to eliminate all forms of waste throughout the supply chain (Shah and Ward 2007). The green supply chain management practices specified by Zhu, Sarkis, and Lai (2008) are specifically designed to eliminate environmental wastes. We argue that lean practices and green practices combine to form a resource advantage for adopting firms. Firms with such combined capabilities gain advantage over competitors based on the general ability to eliminate all forms of waste and the specific ability to eliminate environmental wastes. These abilities allow firms to provide customers with eco-friendly products and services that are produced through environmentally sustainable processes at relatively low costs.

We further argue that lean manufacturing practices and green supply chain management practices are complementary in that waste elimination capabilities emanating from lean practices will enhance a firm's ability to successfully implement green supply chain management practices giving it the additional capability to reduce and/or eliminate environmental wastes associated with its production processes and its products and services. Lean practices and green practices are complementary and synergistic in their impact on environmental and operational performance. This synergy is reflected in the positive impact of implementation of lean practices on the results of mutually or subsequently implemented green practices. More lean leads to more green or vice versa.

3. Justification of the study

There are many research papers that simultaneously address the issues of 'lean' and 'green'. A number of different approaches have been utilised to examine the relationship between the two. These approaches include survey research (Klassen 2000; Rothenberg, Pil, and Maxwell 2001; Zhu and Sarkis 2004; Green et al. 2012; Hajmohammad et al. 2013; Prasad, Khanduja, and Sharma 2016), use of secondary data (King and Lenox 2001; Bergmiller and McCright 2009; Yang, Hong, and Modi 2011; Hong, Roh, and Rawski 2012), literature reviews (Fliedner and Majeske 2010; Mollenkopf et al. 2010; Dües, Tan, and Lim 2013; Hallam and Contreras 2016), interviews (Klassen 2000; Rothenberg, Pil, and Maxwell 2001; Biggs 2009; Campos and Vazquez-Brust 2016), simulation (Diaz-Elsayed et al. 2013; Ugarte, Golden, and Dooley 2016), case studies (Klassen 2000; Larson and Greenwood 2004; Biggs 2009; Miller, Pawloski, and Standridge 2010; Azevedo et al. 2012; Galeazzo, Furlan, and Vinelli 2014; Piercy and Rich 2015; Campos and Vazquez-Brust 2016; Garza-Reyes et al. 2016), value stream mapping (Vinodh, Arvind, and Somanaathan 2011; Garza-Reyes et al. 2016) and conceptual frameworks or models (Simpson and Power 2005; Carvalho, Duarte, and Cruz-Machado 2011; Pampanelli, Found, and Bernardes 2014; Alves and Alves 2015). Data utilised in these studies come from a variety of countries namely the U.S. (Miller, Pawloski, and Standridge 2010; Green et al. 2012), Canada (Hajmohammad et al. 2013), Japan (Rothenberg, Pil, and Maxwell 2001), China (Zhu and Sarkis 2004), India (Prasad, Khanduja, and Sharma 2016), Brazil (Pampanelli, Found, and Bernardes 2014 and Campos and Vazquez-Brust 2016), Mexico (Garza-Reyes et al. 2016), the United Kingdom (Piercy and Rich 2015) and Portugal (Azevedo et al. 2012), representing multiple industries, for example, automotive (Rothenberg, Pil, and Maxwell 2001; Azevedo et al. 2012; Pampanelli, Found, and Bernardes 2014), furniture (Klassen 2000; Miller, Pawloski, and Standridge 2010), intermodal transport (Colicchia, Creazza, and Dallari 2017) and foundry (Prasad, Khanduja, and Sharma 2016).

There is also some variety in order of implementation deemed appropriate by lean/green researchers. Some researchers feel that lean drives green (Larson and Greenwood 2004; Fliedner and Majeske 2010; Dües, Tan, and Lim 2013; Pampanelli, Found, and Bernardes 2014), some that green drives lean (Bergmiller and McCright 2009), some that feel either can go first (Galeazzo, Furlan, and Vinelli 2014; Piercy and Rich 2015) and some who feel that both should be implemented concurrently (Klassen 2000; King and Lenox 2001; Miller, Pawloski, and Standridge 2010; Azevedo et al. 2012; Ng, Low, and Song 2015; Garza-Reyes et al. 2016).

Despite Hajmohammad et al.'s (2013) observation that 'very few studies (if any) have simultaneously addressed environmental management practices, operation/supply chain systems, and environmental performance', Hallam and Contreras (2016) managed to review 60 articles representing 'the most relevant peer-reviewed journal publications covering the integration of Lean and Green management' and noted that most were case studies or conceptual papers with only ten being surveys. They feel that there is little evidence of combined lean and green implementation but the purported synergy between the two is evident in the postulate of some articles. Specifically, they note that an integrated model of the firm relating lean and green is lacking. Along the same lines, Jabbour et al. (2016) note that the literature has yet to reach a definitive consensus on the necessity to integrate green issues in operations for firms to achieve better performance. Thus, the implication is that research on lean/green issues is still under-examined (Piercy and Rich 2015), especially research utilising survey data.

With the exception of one journal article (Green et al. 2012) and one dissertation (Lee 2013) no research was found examining the relationship between environmental performance and operational performance. While much of this work replicates previous published work (the relationship between lean practices and green practices, lean practices and environmental performance, green practices and environmental performance and green practices and operational performance), we find it necessary to revisit these areas to arrive at the unexplored relationship between environmental performance and operational performance, thereby providing a more integrated empirical model.

4. Literature review

4.1 *Lean practices*

Lean manufacturing has seen wide use and a broad scope of interests over the last 40 years. Emiliani (2006) notes that it has been an important route for improving business performance since the late 1970's although the term 'lean' was first used in scholarly research by Krafcik (1988). Interest in the topic became widespread with the publication of *The Machine That Changed the World* (Womack, Jones and Roos 1990) in 1990. Jasti and Kodali (2015) note that 546 research articles in 24 operations research journals were published from 1988 to 2011 so the literature on lean is very deep and does not bear repeating here. Jasti and Kodali (2015), Gupta and Jain (2013) and Stone (2012) provide comprehensive reviews of the literature regarding lean manufacturing.

Over the years lean manufacturing has gone through an evolution of refinement of its principles and practices to a lean business system (Marodin and Saurin 2013). Its main purpose is to produce products without any kind of waste, with waste defined as anything that adds cost from overproduction, waiting, poor quality or unnecessary processing, transportation or inventory, but adds no value. The practices of Just-in-Time, Total Quality Management, Total Preventive Maintenance and Human Resource Management 'bundled' together make up lean production (Shah and Ward 2003).

4.2 *Green practices*

Green manufacturing (environmentally conscious manufacturing) is an element of Green Supply Chain Management, along with green product development, green design, green procurement, green process planning and green transportation (Luthra, Garg, and Haleem 2014) and is a key aspect of achieving sustainability which results in improvement in the 'triple bottom line' of economic, social and environmental responsibility. Green manufacturers adopt processes, practices and techniques that consume less energy and material, reduce potentially harmful wastes through reuse and recycling and prevent pollution at the source. For the green manufacturer, these processes, practices and techniques can result in lower costs, increased productivity and an enhanced image with consumers and the community. Comprehensive literature reviews on the subject are provided by Sambrani and Pol (2016), Sarkis, Zhu, and Lai (2011) and Srivastava (2007).

4.3 *Lean and green*

Hajmohammad et al. (2013) identify lean management as providing capabilities that ease the implementation of environmental practices. Green et al. (2012) recommend assessing lean manufacturing as an antecedent to the implementation of green supply chain management practices. They argue that efforts to eliminate wastes through programmes such as JIT (a primary component of lean manufacturing) support efforts to eliminate environmentally damaging wastes through the implementation of green manufacturing practices. Drohomeretski, Gouvea, and Pinheiro (2014) provide anecdotal evidence that the primary motivation for the implementation of green supply chain management practices in the Brazilian Auto Industry is an emphasis on cost reduction through programmes such as lean manufacturing. Companies adopting lean manufacturing practices are also likely to implement green supply chain management practices. Sarkis (2012) argues that both lean and green initiatives focus on the elimination of wastes throughout the supply chain. Utilising a conceptual framework (Simpson and Power 2005; Pampanelli, Found, and Bernardes 2014) case study (Azevedo et al. 2012), secondary data (Yang, Hong, and Modi 2011) and literature review (Mollenkopf et al. 2010) a positive relationship has been shown to exist between lean practices and green practices. By analysing survey data from a sample of Canadian manufacturing plants, Hajmohammad et al. (2013) found the level of lean management activities to be positively associated with the extent of environmental practices.

4.4 *Lean and environmental performance*

Research in this area is somewhat scarce as Negrao, Godinho Filho, and Marodin (2017) conducted an extensive literature review on lean practices and found only one article relating lean practices to environmental performance. However, through case studies (Larson and Greenwood 2004; Biggs 2009; Azevedo et al. 2012) and analysis of secondary data (Yang, Hong, and Modi 2011; Hong, Roh, and Rawski 2012) support was found for lean supply chain management practices resulting in improved green performance. King and Lenox (2001) found that adoption of lean management practices in the form of ISO 9001 standards and lower maximum inventory levels lead to reductions in waste generation and emissions. However, Hajmohammad et al. (2013), via survey of Canadian firms, found that a positive association between level of lean management activities and environmental performance was not supported. Similarly, Zhu and Sarkis (2004), via survey of Chinese firms, found that the relationship between green practices and environmental performance was not higher in firms with quality management practices and was actually weaker in firms with more JIT adoption. Hallam and Contreras (2016) via literature review, note that 'while both approaches share waste reduction as an objective, Green and Lean management philosophies may also work against each other', possibly by more greenhouse gases emitted by JIT delivery processes. Others note that lean manufacturing alone does not significantly impact environmental performance (Yang, Hong, and Modi 2011) and alone, will never be enough to address all environmental issues (Dües, Tan, and Lim 2013).

4.5 *Green supply chain management practices and environmental performance*

Green supply chain management practices are specifically designed to positively impact environmental performance. Azevedo et al. (2012) and Yang, Hong, and Modi (2011) found support for this from a case study and secondary data, respectively. Analysis of survey data from Brazil (Jabbour et al. 2016), China (Zhu and Sarkis 2004; Lai and Wong 2012), Canada (Hajmohammad et al. 2013) Korea (Lee 2013) and the U.S. (Green et al. 2012) found a significant positive relationship between green supply chain practices and environmental performance.

4.6 *Green supply chain management practices and operational performance*

Although Green et al. (2012) did not assess the direct link between green supply chain management practices and operational performance within the context of their structural model, they report significant positive correlations between multiple practices (internal environmental management, green information systems, green purchasing, cooperation with customers, eco-design and investment recovery) and operational performance. Through analysis of secondary data, Yang, Hong, and Modi (2011) found support for a positive association between green supply chain practices and operational performance as did Klassen and McLaughlin (1996) through an event study. Jabbour et al. (2016) surveyed Brazilian operations/production managers from industrial and manufacturing firms and found green practices to be positively related to operational performance. Yu et al. (2014) surveyed automobile manufacturers in China, and found that three components of green supply chain management are positively and significantly related to multiple forms of operational performance (operating flexibility, delivery, product quality and production cost). Analysis of survey data from Indian firms (Mitra and Datta 2014) revealed environmentally sustainable product design and logistics to be positively related to competitiveness (which included operational performance criteria). Based on a survey of Korean manufacturing firms, Lee (2013) reported a significant link from green supply chain management practices to operational performance. Positive associations were also found by Lai and Wong (2012) who surveyed senior executives of Chinese exporters and Lee, Kim, and Choi (2012) who surveyed operations/supply chain managers of Korean electronics firms.

Finally, a meta-analysis by Golicic and Smith (2013) confirmed that environmental supply chain practices positively influenced operational-based measures of performance.

4.7 *Environmental performance and operational performance*

Research on the impact of environmental performance on operational performance is considerably scarcer in the literature than our other postulates and as such is a much more important contribution to the body of knowledge on the subject. Green et al. (2012), utilising data from U.S. firms, conducted a structural analysis that included the assessment of the impact of environmental performance on operational performance yielding a positive result. Closely related, Lee (2013) reported a significant link from environmental performance to operational performance based on analysis of survey data from Korean manufacturing firms.

5. Hypotheses

In addition to results of conceptual work (Simpson and Power 2005; Pampanelli, Found, and Bernardes 2014), a case study (Azevedo et al. 2012), use of secondary data (Yang, Hong, and Modi 2011) and literature review (Mollenkopf et al. 2010) and a Canadian survey (Hajmohammad et al. 2013), we propose to expand the body of knowledge by utilising survey data from U.S. manufacturing firms. We propose that:

H1: Lean manufacturing practices are positively associated with green supply chain management practices.

Further survey research, specifically utilising firms from a different country (U.S.), could supplement past findings and help to clarify conflicting findings in research regarding lean practices and environmental performance. Since lean manufacturing incorporates systems, processes and practices that support the elimination of all forms of waste and existence of these systems, processes and practices should enhance and support an organisation's ability to implement green practices that are specifically designed to eliminate environmental wastes, we propose that:

H2: Lean manufacturing practices are positively associated with environmental performance.

In support of findings from scarce survey-based studies regarding the relationship between green supply chain management practices and environmental performance (Zhu and Sarkis 2004; Hajmohammad et al. 2013; Lai and Wong 2012; Lee 2013; Jabbour et al. 2016) and even scarcer survey-research utilising data from U.S. firms (Green et al. 2012), we theorise that green supply chain management practices are antecedent to environmental performance:

H3: Green supply chain management practices are positively associated with environmental performance.

The association between lean manufacturing practices and performance has been widely researched as evidenced by an exhaustive literature review of the subject by Negrao, Godinho Filho, and Marodin (2017). They found 41 articles that suggested a positive effect of lean practices in at least one operational, financial and/or environmental performance metric and only three studies that indicated some lean practices had a negative effect on operational or financial performance. Even though it has been highly researched previously, we include this relationship in our study as it is embedded in the theorised model. Therefore:

H4: Lean manufacturing practices are positively associated with operational performance.

Even though there are previous studies regarding the relationship between green supply chain practices and operational performance (see Literature Review), this work includes the same in order to provide a more complete integrated model. Therefore, in replication of previous studies, but uniquely using data from U.S. firms, we propose that:

H5: Green supply chain management practices are positively associated with operational performance.

Using complementarity theory we argue that, together, lean manufacturing practices and green supply chain management practices will synergistically produce superior results. Only Green et al. (2012) and Lee (2013) have researched the impact of environmental performance on operational performance. Green et al. (2012) found a positive impact of environmental performance on operational performance while Lee (2013) reported finding a significant link from environmental performance to operational performance. Taken together, logic and these results support the claim that environmental performance is positively associated with operational performance. Hence:

H6: Environmental performance is positively associated with operational performance.

6. Theorised model

The theoretical model is displayed in Figure 1. The model incorporates four constructs and six hypotheses. The constructs definitions as they are applied in this study are presented in Table 1. All hypothesised relationships are positive. The model is designed to facilitate assessment of the combined impact of lean manufacturing practices and green supply chain management practices on environmental sustainability.

7. Methodology

This study uses a well-established survey methodology (Inman et al. 2011; Green et al. 2012) in which the data collection is managed by a third-party data collection service. A structural equation modelling (SEM) methodology is followed to analyse the assembled data-set, test the individual hypotheses within the model and to assess the fit of the theorised model to the data. Partial Least Squares SEM is used to specifically test each of the hypotheses within the model as recommended by Wetzels, Odekerken-Schröder, and van Oppen (2009) and in a manner consistent that found in the existing literature (Clark, Toms, and Green 2014; Green et al. 2017). Akter, Wamba, and Dewan (2017) recommend using PLS/SEM for assessing complex structural models to facilitate completeness and capture reality. SmartPLS 2.0 software (Ringle, Wende, and Will 2005) is used to conduct the PLS analysis. Co-variance-based SEM (Lisrel 8.8) is used to assess the fit of the overall model. The use of co-variance-based SEM to assess overall model fit is also well established in the literature (Inman et al. 2011; Green et al. 2012). This combination of SEM methods is based on descriptions of the appropriate uses of PLS and co-variance-based SEM (PLS for hypothesis testing and co-variance based for model testing) by Hair, Ringle, and Sarstedt (2011). Using both PLS and co-variance-based approaches supports the appropriate testing of individual hypotheses within the context of a structural model and also the appropriate assessment of the overall fit of the structural model. It is also interesting to compare the results of the alternative SEM methods.

7.1 *Data collection*

Data were collected from a sample of 182 manufacturing managers working for U.S. manufacturing plants through an online data collection service. One thousand one hundred and forty-six managers were originally contacted and data were ultimately collected from the 182 manufacturing managers for an effective response rate of 15.9%. Sample demographics are displayed in Table 2.

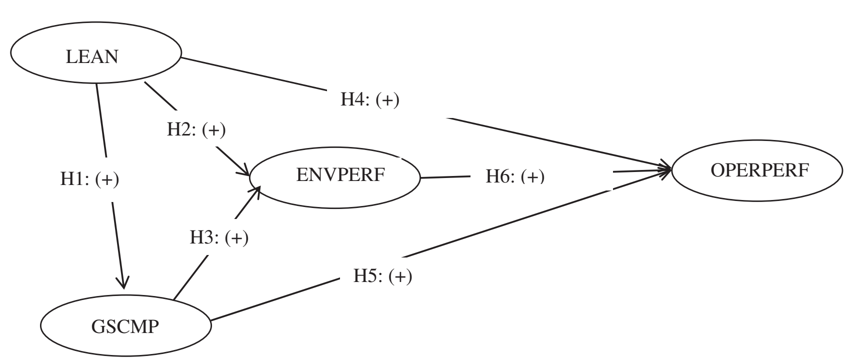

Figure 1. Theoretical Model with Hypotheses.
Notes: LEAN – Lean Manufacturing Practices; GSCMP – Green Supply Chain Management Practices; ENVPERF – Environmental Performance; OPERPERF – Operational Performance.

Table 1. Construct definitions.

Construct	Definition
Green Supply Chain Management Practices	A management improvement programme comprised of internal environmental management, green purchasing, cooperation with customers, eco-design and investment recovery practices designed to integrate and coordinate the environmental sustainability efforts of all supply chain partners for the purpose of eliminating all forms of environmental waste from supply chain processes (Zhu, Sarkis, and Lai 2008; Green et al. 2012)
Lean Manufacturing Practices	A management improvement programme comprised of lean practices with suppliers and customers that emphasise setup time reduction, pull systems, continuous flow, statistical process control, preventive maintenance and employee involvement designed to eliminate all forms of waste from all supply chain processes (Shah and Ward 2003, 2007)
Environmental Performance	Environmental performance relates the ability of manufacturing plants to reduce air emissions, effluent waste and solid wastes and the ability to decrease consumption of hazardous and toxic materials (Zhu, Sarkis, and Lai 2008)
Operational Performance	Operational performance relates to the manufacturing plant's capabilities to more efficiently produce and deliver products to customers (Zhu, Sarkis, and Lai 2008)

Table 2. Sample demographics summary.

Title	Number
Owner	7
Vice-President	38
Plant Manager	10
Operations Manager	56
Purchasing Manager	17
Logistics Manager	13
Maintenance Manager	3
Sales Manager	4
Engineering Manager	8
Industrial Waste Manager	2
Inventory Manager	1
Quality Manager	7
Research and Development Manager	1
Other Manager	15
Total	182
Industry Category	
Food Manufacturing	14
Beverage and Tobacco Product Manufacturing	3
Textile Mills	6
Apparel Manufacturing	1
Wood Product Manufacturing	3
Paper Manufacturing	1
Printing and Related Support Activities	6
Petroleum and Coal Products Manufacturing	2
Chemical Manufacturing	16
Plastics and Rubber Products Manufacturing	6
Non-metallic Mineral Product Manufacturing	2
Primary Metal Manufacturing	7
Fabricated Metal Product Manufacturing	18
Machinery Manufacturing	18
Computer and Electronic Product Manufacturing	7
Electrical Equipment, Appliance and Component Manufacturing	9
Transportation Equipment Manufacturing	11
Miscellaneous Manufacturing	52
Total	182
Mean Years in Current Position	11.53
Mean Number of Plant Employees	964.07

7.2 *Measurement scales*

The lean manufacturing practices construct is a second-order construct with dimensions of lean manufacturing practices related to suppliers, customers, setup times, pull systems, preventive maintenance, employee involvement, statistical process control and continuous flow as originally specified by Shah and Ward (2007). The green supply chain management practices construct is a second-order construct with dimensions of internal environmental management, green purchasing, cooperation with customers, eco-design and investment recovery as originally specified by Zhu, Sarkis, and Lai (2008). The environmental performance and operational performance scales were also originally developed by Zhu, Sarkis, and Lai (2008). All measurement scales are displayed in Appendix 1.

7.3 *Non-response bias assessment*

To assess non-response bias, responses for the study variables from first-wave responders (54%) were compared with responses from second-wave responders (46%). A lack of significant differences between responses from the early and late responders supports a claim that non-response bias has a minimal impact in the data-set (Armstrong and Overton 1977).

7.4 *Common method bias assessment*

The data collection for this study included measurement scales that are not included in this study. The smallest correlation among all of the variables in the larger data-set is 0.36 as compared with the smallest correlation among the variable relationships specified in the structural model of 0.50 The significant difference at the 0.01 level between these two correlations supports the claim that common method bias does not negatively impact the data-set (Lindell and Brandt 2000; Lindell and Whitney 2001; Malhotra, Patil, and Kim 2007).

7.5 *Measurement scale validity and reliability*

All measurement scales were established and assessed in previous research (Shah and Ward 2007; Zhu, Sarkis, and Lai 2008) and are therefore considered to exhibit sufficient content reliability. All standardised factor loadings for the first-order constructs are greater than 0.70 supporting a claim of sufficient convergent validity (Chiang, Kocabasoglu-Hillmer, and Suresh 2012). Square root of the average variance extracted values for first-order constructs greater than correlations with other first-order constructs signify sufficient discriminant validity (Wetzels, Odekerken-Schröder, and van Oppen 2009). This is the case with one exception. The square root of the average variance extracted for the lean-with-suppliers first-order construct is less than the correlations with lean with customers, lean employee involvement and lean-statistical process control. Since this exception is between first-order constructs that make up lean production, discriminant validity is considered sufficient. Cronbach's alpha, composite reliability and average variance extracted values all exceed the respective recommended minimums of 0.70, 0.70 and 0.50 (Garver and Mentzer 1999) supporting a claim of sufficient reliability. Reliability scores, correlations among first-order constructs and square root of average variance extracted values are displayed in Table 3.

The measurement scales are considered sufficiently valid and reliable. Non-response bias and common method bias do not negatively impact the data-set. Structural equation modelling results, and hypotheses test results are presented in the following section. The subsequent section includes results from both PLS/SEM and co-variance-based/SEM. It is necessary to both assess the hypotheses embedded in the structural model and to assess the fit of the overall model for theory testing purposes. PLS/SEM is best suited for hypothesis testing and co-variance-based/SEM is best suited for model fit and theory testing (Henseler, Ringle, and Sinkovics 2009; Hair, Ringle, and Sarstedt 2011).

8. Results

8.1 *PLS/SEM results*

A PLS/SEM statistical analysis methodology is employed because of the use of second-order constructs in the model and because our primary objective is to test the hypotheses in the model. PLS results are displayed in Figure 2 and support for the hypotheses is summarised in Table 4. Hypotheses 1 through 4 (LEAN → GSCMP, LEAN → ENVPERF, GSCMP → ENVPERF, LEAN → OPERPERF) and 6 (ENVPERF → OPERPERF) are supported. Hypothesis 5 (GSCMP → OPERPERF) is not supported.

Table 3. Reliability scores and correlations among first-order latent constructs.

Variables	CA	CR	AV	CC	ED	GP	IE	IR	LC	LE	LF	LM	LP	LS	LT	LW	EP	OP
CC	0.94	0.96	0.86	**0.93**														
ED	0.93	0.96	0.88	0.85	**0.94**													
GP	0.95	0.96	0.80	0.84	0.75	**0.89**												
IE	0.96	0.97	0.80	0.72	0.66	0.74	**0.89**											
IR	0.86	0.91	0.78	0.66	0.70	0.67	0.67	**0.88**										
LC	0.94	0.95	0.80	0.60	0.52	0.51	0.61	0.57	**0.89**									
LE	0.93	0.95	0.82	0.65	0.59	0.63	0.66	0.62	0.68	**0.91**								
LF	0.92	0.94	0.80	0.62	0.52	0.64	0.63	0.58	0.72	0.69	**0.89**							
LM	0.90	0.93	0.76	0.61	0.52	0.57	0.65	0.56	0.65	0.76	0.67	**0.87**						
LP	0.90	0.93	0.77	0.62	0.53	0.65	0.64	0.58	0.61	0.63	0.77	0.60	**0.87**					
LS	0.94	0.95	0.80	0.61	0.55	0.68	0.65	0.62	0.62	0.71	0.73	0.70	0.75	**0.89**				
LT	0.87	0.92	0.79	0.64	0.65	0.61	0.63	0.63	0.62	0.70	0.75	0.68	0.71	0.71	**0.89**			
LW	0.94	0.94	0.59	0.70	0.64	0.73	0.67	0.71	0.79	0.78	0.74	0.73	0.72	0.77	0.72	**0.76**		
EP	0.94	0.95	0.76	0.60	0.60	0.56	0.64	0.60	0.50	0.59	0.51	0.60	0.52	0.51	0.55	0.58	**0.87**	
OP	0.92	0.94	0.71	0.56	0.56	0.51	0.49	0.52	0.59	0.56	0.52	0.56	0.55	0.50	0.59	0.63	0.66	**0.84**

Notes: CA – Cronbach's Alpha; CC – Cooperation with Customers; CR – Composite Reliability; ED – Eco-design; AV – Average Variance Extracted; GP – Green Purchasing; EP – Environmental Performance; IE – Internal Environmental Management; OP – Operational Performance; IR – Investment Recovery; LS – Lean Statistical Process Control; LC – Lean with Customers; LP – Lean Pull Production; LF – Lean Continuous Flow; LT – Lean Setup; LE – Lean Employee Involvement; LM – Lean Preventive Maintenance; LW – Lean with Suppliers.
Square root of average variance extracted in bold on diagonal.

Table 4. Structural model PLS results.

Model Link	Std. coefficients	Support
LEAN → GSCMP	+0.81**	H1: supported
LEAN → ENVPERF	+0.24 *	H2: supported
GSCMP → ENVPERF	+0.48**	H3: supported
LEAN → OPERPERF	+0.44**	H4: supported
GSCMP → OPERPERF	-0.06^{ns}	H5: not supported
ENVPERF → OPERPERF	+0.45**	H6: supported

Notes: LEAN – Lean manufacturing; GSCMP – Green supply chain management practices; ENVPERF – Environmental performance; OPERPERF – Operational performance.
**sig. at 0.01 level.
*sig. at 0.05 level.
^{ns}non-significant.

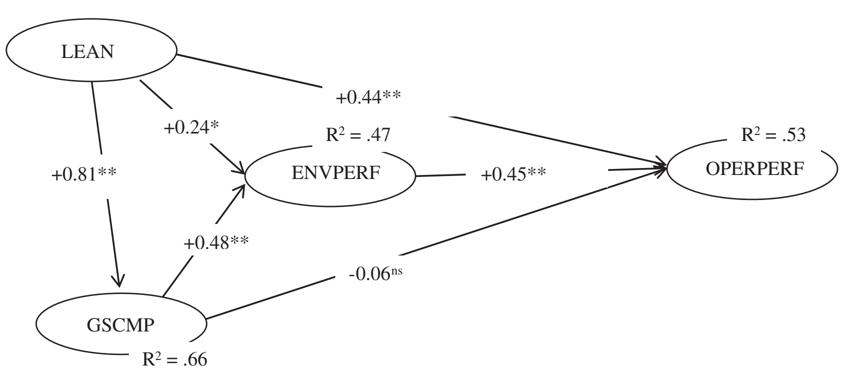

Figure 2. PLS SEM results.
Notes: LEAN – Lean Manufacturing Practices; GSCMP – Green Supply Chain Management Practices; ENVPERF – Environmental Performance; OPERPERF – Operational Performance; **sig. at 0.01 level; *sig. at 0.05 level; ^{ns}non-significant.

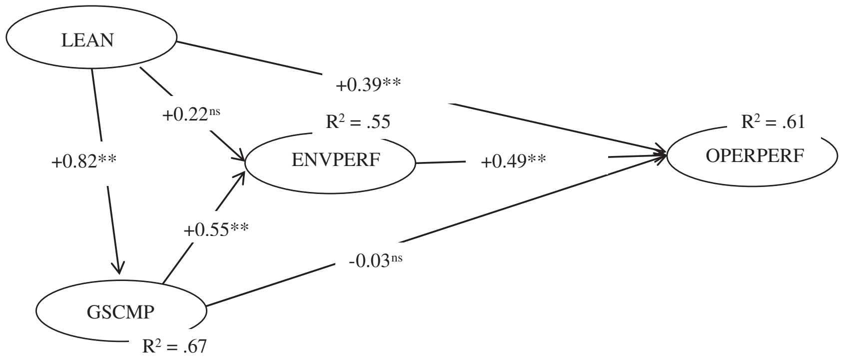

Figure 3. Covariance-based SEM Results.
Notes: Relative Chi-Square = 0.33; Chi Square *P*-value = 1.00; RMSEA = 0.00; NFI = 0.98; SRMR = 0.03; GFI = 0.96; LEAN – Lean Manufacturing Practices; GSCMP – Green Supply Chain Management Practices; ENVPERF – Environmental Performance; OPERPERF – Operational Performance; **sig. at 0.01 level; *sig. at 0.05 level; ^{ns}non-significant.

Table 5. Comparison of study findings.

Hypothesis	Supported	Not supported	This study
Positive relationship between Lean Supply Chain Practices and Green Supply Chain Practices	Pampanelli, Found, and Bernardes (2014); Hajmohammad et al. (2013); Azevedo et al. (2012); Yang, Hong, and Modi (2011); Mollenkopf et al. (2010); Simpson and Power (2005)		Supported
Positive relationship between Lean Supply Chain Management practices and Environmental Performance	Azevedo et al. (2012); Hong, Roh, and Rawski (2012); Yang, Hong, and Modi (2011); Biggs (2009); Larson and Greenwood (2004)	Hajmohammad et al. (2013); Zhu and Sarkis (2004)	Supported*
Positive relationship between Green Supply Chain Management Practices and Environmental Performance	Jabbour et al. (2016); Hajmohammad et al. (2013); Lai and Wong (2012); Lee (2013); Azevedo et al. (2012); Green et al. (2012); Yang, Hong, and Modi (2011); Zhu and Sarkis (2004)		Supported
Positive relationship between Lean Manufacturing Practices and Operational Performance	Negrao, Godinho Filho, and Marodin (2017) (extensive lit review)	Bortolotti, Boscari, and Romano (2013); Chen and Tan (2013); Kadipasaoglu, Peixoto, and Khumawala. (1999)	Supported
Positive relationship between Green Supply Chain Management Practices and Operational Performance	Jabbour et al. (2016); Chavez et al. (2015); Mitra and Datta (2014); Golicic and Smith (2013) (extensive lit review); Lee (2013); Lai and Wong (2012); Lee, Kim, and Choi (2012); Yang, Hong, and Modi (2011); Klassen and McLaughlin (1996)		Direct impact not supported, impact of GSCMP on Operational Performance is indirect through Environmental Performance
Positive relationship between Environmental Performance and Operational Performance	Lee (2013); Green et al. (2012)		Supported**

*Although lean practices directly affected environmental performance, the indirect effect of lean on environmental performance was stronger, i.e. lean and green are complementary.
**Indicates an indirect association between green practices and operational performance through environmental performance. See Section 9.1.

Lean manufacturing practices combine with green supply chain management practices to positively impact both environmental performance and operational performance. Forty-seven per cent of the variation in environmental performance is explained by the variation in lean practices and green practices combined. The successful implementation of lean practices supports implementation of green practices. The association is positive and very strong. The strong positive association is expected since green practices have formed as a subset of lean practices. Lean practices are aimed at eliminating all forms of waste throughout the supply chain, while green practices are focused on the elimination of environmental wastes as a specific category of wastes. Although the PLS results indicate that lean practices directly affect environmental performance, the indirect effect of lean practices on environmental performance through green practices is stronger which indicates complementarity. The direct effect is +0.24 (sig. at the 0.05 level), while the indirect effect is +0.39 (+0.81 times +0.48; sig. at the 0.01 level).

Fifty-three per cent of the variation in operational performance is explained by the combined impact of lean practices, green practices and environmental performance. Lean practices both directly and indirectly impact operational performance. The direct effect (+0.44) is positive, moderately strong and significant at the 0.01 level. The indirect effect (+0.11 = +0.24 times +0.45) of lean practices through environmental performance is positive, weak and significant at the 0.05 level. Importantly, the PLS/SEM results indicate that the effect of green practices on operational performance is indirect through environmental performance, rather than direct. The indirect effect of +0.22 (+0.48 times +0.45) is positive and significant at the 0.01 level.

8.2 *Co-variance-based/SEM results*

Although we believe that the use of PLS/SEM statistical analysis is appropriate, we also understand that there is some conflict in the literature as to which SEM methodology, PLS/SEM or co-variance-based/SEM, is best for model testing. While we believe that PLS/SEM is more appropriate for this study, we also present the co-variance-based/SEM results from Lisrel 8.8 for comparison in Figure 3.

Please note that a comparison of the PLS/SEM results with the co-variance-based/SEM results reveals only one minor difference. The standardised coefficient for the lean practices to environmental performance link is +0.24 (sig. at the 0.05 level) based on the PLS/SEM results compared to the standardised coefficient of +0.22 (non-significant) based on the co-variance-based/SEM results. Otherwise, all standardised coefficients are similar with comparable significance levels between the two methods. It should be noted that the model fits the data relatively well based on the values of these co-variance-based/SEM fit indices: chi-square of 0.33, RMSEA = 0.00; NFI = 0.98; SRMR = 0.03; and GFI = 0.96.

9. Conclusions

9.1 *Discussion of findings*

We argue that lean manufacturing practices are positively associated with green supply chain management practices. Consistent with past research we found support for the proposals that lean manufacturing practices are positively associated with green supply chain management practices, lean manufacturing practices are positively associated with environmental performance, green supply chain management practices are positively associated with environmental performance, lean manufacturing practices are positively associated with operational performance. Noteworthy is the finding that, although the PLS results indicate that lean practices directly affect environmental performance, the indirect effect of lean practices on environmental performance through green practices was stronger supporting our claim that lean practices and green practices are complementary. The primary contribution of this study, is the finding that no support was found for the idea that green supply chain management practices are positively associated with operational performance. This is in contrast to past research (see Table 5) utilising survey data from Brazil (Jabbour et al. 2016), China (Lai and Wong 2012; Yu et al. 2014), India (Mitra and Datta 2014) and Korea (Lee 2013). However, environmental performance is found to be positively associated with operational performance, indicating an indirect association between green practices and operational performance through environmental performance. In other words, improvement in operational performance does not come directly from implementation of green practices but rather from improving environmental performance as a result of implementation of green practices. At first glance, this is circular logic, but, it suggests that firms merely adding green practices to lean practices without an improvement in environmental performance may not be receiving the full benefit of the complementarity between lean and green practices. Despite the compatibility of the two sets of practices, firms can still fail to strategically capitalise on the environmental benefits that are a by-product of lean processes (Larson and Greenwood 2004). For example, Boeing had significant difficulty applying lean to environmental processes (Larson and Greenwood 2004). Green practices implementation can result in some firms outperforming others as a result of their ability to leverage their resources and possibly possession of a unique set of resources (Shi et al. 2012) as is consistent with the resource-based view (RBV).

The literature indicates that lean transformations appear to be more successful when aligned throughout the enterprise (Stone 2012). 'Side-by-side' green and lean practices may fail to realise the competitive advantage of the complementarity provided by fully integrated systems by concentrating 'on what is the same about sustainable supply chain management with much less emphasis on what, if anything, might be truly unique'. (Pagell and Wu 2009) Carter and Rogers (2008) state that '… organisations that become sustainable enterprises do not simply overlay sustainability initiatives with corporate strategies'. Measures of environmental performance should be included in any integrated model of lean practices and green practices to ensure that improvements in operational performance are realised as an indirect product of green practices (through environmental performance) rather than from some other strategic initiative, e.g. lean. The same holds true for negative results arising from integrating lean and green practices. Failure to classify lean properly can make it difficult to identify sustainability benefits leading to the identification of incorrect negative associations (Piercy and Rich 2015) whereas direct measurement of environmental performance could preclude this.

Lean practices and green practices are organisational competencies that combine to reduce product and service costs through the elimination of wastes and enhance environmental sustainability by supporting the production of eco-friendly products demanded by customers. The results of our study support the case for the implementation of both lean practices and green practices. While the implementation of lean practices without green practices will result in significantly improved operational performance, the impact of lean practices on environmental performance is slight. Combining lean practices and green practices significantly improves environmental performance while also boosting operational performance incrementally, notably consistent with complementarity theory.

Manufacturing managers striving to improve both the economic sustainability and environmental sustainability of their firms should follow the implementation of lean manufacturing practices with the implementation of green supply chain practices. Lean and green combine (1) to improve operational performance through the elimination of wastes thereby reducing costs and enhancing economic sustainability, (2) to improve environmental performance through the elimination of environmental wastes in particular thereby, enhancing the environmental sustainability of the firm, thereby, providing the firm with possibly unique resources (resource heterogeneity) that are not readily or easily obtainable (imperfectly mobile) as is consistent with synergies related to complementarity theory and (3) to improve operational performance from complementarity or the synergy produced by the full integration of lean practices and green practices.

9.2 *Limitations of the study*

This study focuses on the impact of lean and green practices within the context of the manufacturing sector within the U.S. limiting the degree to which the results and conclusions can be generalised. There is a minor difference between the PLS/SEM and co-variance-based/SEM related to the significance of the standardised coefficient for the lean practices to environmental performance link. The standardised coefficients are both positive (+0.24 versus + 0.22). The larger coefficient is significant at the 0.05 level in the PLS/SEM results while the smaller coefficient is non-significant in the co-variance-based/SEM results.

9.3 *Future research*

To generalise the results outside the manufacturing sector, it is important to replicate this study with samples from the services sector. Also, future research could utilise a more complex model such as that recommended by Hallam and Contreras (2016). We recommend a more comprehensive structural model that incorporates additional antecedents to environmental performance such as supply chain management strategy and information sharing through enterprise resource planning systems. As a result of this study, it is advisable to include measures of environmental performance between green practices and operational performance on any research model investigating the integration of lean and green practices.

Jasti and Kodali (2015) emphasise the need to build theory regarding lean, so, it would be helpful if future research were built on different theories. The research on lean practices and the research on green practices include numerous studies built on various theories (RBV, NRBV, stakeholder theory, institution theory, resource advantage theory, etc.) but much of the work done regarding the integration of lean and green omits any discussion of theory or offers a theory section that is mostly literature review. Also, researchers tend to restrict their work to tangible benefits (Anand and Kodali 2008) and elimination of a few lean wastes (Anand and Kodali 2008), so future research could focus on intangible benefits of lean and green integration and a more complete set of wastes. Finally, investigation of contingency factors affecting the performance of the integration of lean and green practices is needed (Schmidt, Foerstl, and Schaltenbrand 2017).

9.4 *Implications for practitioners*

Manufacturing managers working to improve the environmental sustainability of their firms should implement lean manufacturing practices in combination with green supply chain management practices. The sets of practices combine to improve both environmental performance and operational performance. Managers can expect reductions in costs associated with waste elimination generally and enhanced environmental sustainability associated with the elimination of environmental wastes specifically and as such should not overlook the importance of measuring environmental performance. While lean practices may result is some improvement in environmental performance when implemented in isolation, combining lean practices with green practices provides significant improvement in environmental performance.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix 1. Measurement scales

Lean Practices Related to Suppliers (Shah and Ward 2007)
Please indicate the extent of implementation of each of the following practices in your plant. (1 = no implementation; 2 = little implementation; 3 = some implementation; 4 = extensive implementation; 5 = complete implementation)
1. We frequently are in close contact with our suppliers
2. We give our suppliers feedback on quality and delivery performance
3. We strive to establish long-term relationships with our suppliers
4. Suppliers are directly involved in the new product development process
5. Our key suppliers deliver to our plant on a JIT basis
6. We have a formal supplier certification programme
7. Our suppliers are contractually committed to annual cost reductions
8. Our key suppliers are located in close proximity to our plant
9. We have corporate-level communication on important issues with key suppliers
10. We take active steps to reduce the number of suppliers in each category
11. Our key suppliers manage our inventory
12. We evaluate suppliers on the basis of total cost and not on per unit price

Lean Practices Related to Customers (Shah and Ward 2007)
Please indicate the extent of implementation of each of the following practices in your plant. (1 = no implementation; 2 = little implementation; 3 = some implementation; 4 = extensive implementation; 5 = complete implementation)
1. We frequently are in close contact with our customers
2. Our customers give us feedback on quality and delivery performance
3. Our customers are actively involved in current and future product offerings
4. Our customers are directly involved in current and future product offerings
5. Our customers frequently share current and future demand information with our marketing department

Lean Practices Related to Pull Practices (Shah and Ward 2007)
Please indicate the extent of implementation of each of the following practices in your plant. (1 = no implementation; 2 = little implementation; 3 = some implementation; 4 = extensive implementation; 5 = complete implementation)
1. Production is 'pulled' by the shipment of finished goods
2. Production at stations is 'pulled' by the current demand at the next station
3. We use a 'pull' production system
4. We use Kanban squares or containers of signals for production control

Lean Practices Related to Continuous Flow (Shah and Ward 2007)
Please indicate the extent of implementation of each of the following practices in your plant. (1 = no implementation; 2 = little implementation; 3 = some implementation; 4 = extensive implementation; 5 = complete implementation)
1. Products are classified into groups with similar processing requirements
2. Products are classified into groups with similar routing requirements
3. Equipment is grouped to produce a continuous flow of families of products
4. Families of products determine our factory layout

Lean Practices Related to Setup (Shah and Ward 2007)
Please indicate the extent of implementation of each of the following practices in your plant. (1 = no implementation; 2 = little implementation; 3 = some implementation; 4 = extensive implementation; 5 = complete implementation)
1. Our employees practice setups to reduce the time required
2. We are working to lower setup times in our plant
3. We have low setup times of equipment in our plant

Lean Practices Related to Statistical Process Control (Shah and Ward 2007)
Please indicate the extent of implementation of each of the following practices in your plant. (1 = no implementation; 2 = little implementation; 3 = some implementation; 4 = extensive implementation; 5 = complete implementation)
1. Large number of equipment / processes on shop floor are currently under SPC
2. Extensive use of statistical techniques to reduce process variance
3. Charts showing defect rates are used as tools on the shop floor
4. We use fishbone type diagrams to identify causes of quality problems
5. We conduct product capability studies before product launch

Lean Practices Related to Employee Involvement (Shah and Ward 2007)
Please indicate the extent of implementation of each of the following practices in your plant. (1 = no implementation; 2 = little implementation; 3 = some implementation; 4 = extensive implementation; 5 = complete implementation)
1. Shop floor employees are key to problem solving teams
2. Shop floor employees drive suggestion programmes
3. Shop floor employees lead product/process improvement efforts
4. Shop floor employees undergo cross functional training

Lean Practices Related to Preventive Maintenance (Shah and Ward 2007)
Please indicate the extent of implementation of each of the following practices in your plant. (1 = no implementation; 2 = little implementation; 3 = some implementation; 4 = extensive implementation; 5 = complete implementation)
1. We dedicate a portion of every day to planned equipment maintenance related activities
2. We maintain all of our equipment regularly
3. We maintain excellent records of all equipment maintenance related activities
4. We post equipment maintenance records on shop floor for active sharing with employees

(*Continued*)

Appendix1. (*Continued*)

Internal Environmental Management (Zhu, Sarkis, and Lai 2008)

Please indicate the extent to which you perceive that your plant is implementing each of the following. (five-point scale: 1 = not considering it; 2 = planning to consider it; 3 = considering it currently; 4 = initiating implementation; 5 = implementing successfully)

1. Commitment of GSCM from senior managers
2. Support for GSCM from mid-level managers
3. Cross-functional cooperation for environmental improvements
4. Total quality environmental management
5. Environmental compliance and auditing programmes
6. ISO 14,001 certification
7. Environmental Management Systems

Green Purchasing (Zhu, Sarkis, and Lai 2008)

Please indicate the extent to which you perceive that your plant is implementing each of the following. (five-point scale: 1 = not considering it; 2 = planning to consider it; 3 = considering it currently; 4 = initiating implementation; 5 = implementing successfully)

1. Eco labelling of products
2. Cooperation with suppliers for environmental objectives
3. Environmental audit of suppliers' internal management
4. Suppliers' ISO 14,000 certification
5. Second-tier supplier environmentally friendly practice evaluation
6. Providing design specification to suppliers that include environmental requirements for purchased item

Cooperation with Customers (Zhu, Sarkis, and Lai 2008)

Please indicate the extent to which you perceive that your plant is implementing each of the following. (five-point scale: 1 = not considering it; 2 = planning to consider it; 3 = considering it currently; 4 = initiating implementation; 5 = implementing successfully)

1. Cooperation with customers for eco design
2. Cooperation with customers for cleaner production
3. Cooperation with customers for green packaging
4. Cooperation with customers for using less energy during product transportation

Eco-design (Zhu, Sarkis, and Lai 2008)

Please indicate the extent to which you perceive that your plant is implementing each of the following. (five-point scale: 1 = not considering it; 2 = planning to consider it; 3 = considering it currently; 4 = initiating implementation; 5 = implementing successfully)

1. Design of products for reduced consumption of material/energy
2. Design of products for reuse, recycle, recovery of material and/or component parts
3. Design of products to avoid or reduce use of hazardous products and/or their manufacturing process

Investment recovery (Zhu, Sarkis, and Lai 2008)

Please indicate the extent to which you perceive that your plant is implementing each of the following during the past year. (five-point scale: 1 = not considering it; 2 = planning to consider it; 3 = considering it currently; 4 = initiating implementation; 5 = implementing successfully)

1. Investment recovery (sale) of excess inventories/materials
2. Sale of scrap and used materials
3. Sale of excess capital equipment

Environmental Performance (Zhu, Sarkis, and Lai 2008)

Please indicate the extent to which you perceive that your plant has achieved each of the following during the past year. (five-point scale: 1 = not at all; 2 = a little bit; 3 = to some degree; 4 = relatively significant; 5 = significant)

1. Reduction of air emissions
2. Reduction of effluent waste
3. Reduction of solid wastes
4. Decrease in consumption for hazardous/harmful/toxic materials
5. Decrease in frequency for environmental accidents
6. Improvement in an enterprise's environmental situation

Operational Performance (Zhu, Sarkis, and Lai 2008)

Please indicate the extent to which you perceive that your plant has achieved each of the following during the past year. (five-point scale: 1 = not at all; 2 = a little bit; 3 = to some degree; 4 = relatively significant; 5 = significant)

1. Increase in the amount of goods delivered on time
2. Decrease in inventory levels
3. Decrease in scrap rate
4. Increase in product quality
5. Increase in product line
6. Improved capacity utilisation