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ORIGINAL PAPER

Structural equation modeling of sustainable manufacturing practices

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Abstract The purpose of this research study is to study the sustainable manufacturing practices across industrial sectors and to identify the critical factors for its success implementation. In spite of the fact that sustainable manufacturing has been frequently promoted as a means of improving business competitiveness, small empirical evidence exists in the literature validating its positive link with organizational performance. Sustainable manufacturing practices enable the manufacturing organizations to survive in the competitive environment. For this purpose, empirical data are collected to measure the sustainable manufacturing practices prevailing across different industries located in Tamil Nadu, India. Structural equation modeling (SEM) technique is used to build the measurement and structural models. After that, statistical estimates are used to validate the built model. The data analysis enables the acceptance or rejection of the hypothesis that has been stated on the basis of structural model. The results show the correlation between sustainable manufacturing practices and organizational performance among the industries being surveyed.

Keywords Sustainable manufacturing · Manufacturing systems · Structural equation modeling · Organizational performance

Introduction

Growing businesses recognize environmental consciousness as an important concept for surviving in the competitive world (Bevilacqua et al. 2007). They have been forced to adopt practices that are designed in a manner to keep the environment safety and minimize energy utilization. Sustainable organization also reduces production costs and prevents environmental problems for maintaining the green and clean atmosphere (Senthilkumaran et al. 2001). Green system integrates product and process design issues with manufacturing planning and control problems in such a manner to identify, quantify, assess, and manage the flow of environmental waste with the goal of reducing the environmental impact (Azzone and Noci 1996). Though sustainable manufacturing is widely regarded as a business strategy, few researchers have concentrated on the validation of its positive link with business performance (Singh et al. 2006; Detty and Yingling 2000). One of the vague questions is that how a manufacturer can identify tools and techniques and the relevant capabilities and abilities to become sustainable (Liping et al. 2009). There are several important issues that need to be addressed to understand how sustainable manufacturing be achieved with clarity of purpose, focus, and goals. On the basis of thorough literature review, a conceptual model of sustainable manufacturing is presented which summarizes the links between sustainability drivers, enablers, and outcomes. Structural equation modeling (SEM) is a multivariate statistical analysis technique used to analyze the structural relationships. SEM technique is the combination of factor analysis and multiple regression analysis, and it is used to analyze the structural relationship between measured variables and latent constructs (Tenenhaus et al. 2005a). On the basis of the developed model, research hypotheses have been formulated. The proposed hypotheses have been tested to empirically validate the proposed model by means of conducting a survey among 50 small and medium enterprises (SMEs) located in Tamil Nadu, India. The research hypotheses considered in

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the study include the study of significant correlation between environmental, economic, and social sustainability.

Literature review

The literature has been reviewed from the perspectives of sustainable manufacturing and SEM applications.

Literature review on sustainable manufacturing

Gungor and Gupta (1999) have presented environmentally conscious manufacturing and product recovery (ECMPRO). ECMPRO involves integrating environmental thinking into new product development including design, material selection, manufacturing processes, and delivery of the product to the consumers, plus the end-of-life management of the product after its useful life. Kaebernick et al. (2003) have presented the integration of environmental requirements throughout the entire lifetime of a product. They presented the concept of an approach to product development, based on a paradigm for sustainable manufacturing. Nagel and Tomiyama (2004) have presented 'Design for environment' in the context of design of manufacturing systems. They have outlined the air emission and waste profile of 25 manufacturing system of printed boards. They have presented a concept when a manufacturing system uses less resource and generate less waste and emissions and the environmental balance measured and managed with information technology, the system becomes sustainable and intelligent. Ijomah (2007) has presented a process of bringing used products to a 'like-new' functional state with warranty to match is being regarded as a vital strategy in waste management and environmentally conscious management. The author has presented an outline of the lements of the remanufacturing concept to improve the robustness of design-for-remanufacturing (DFRem). Rusinko (2007) has presented an evaluation of environmentally sustainable manufacturing practice and their impact on competitive outcomes. The author presented an exploratory study of the relationship between specific environmentally sustainable manufacturing practices and specific competitive outcomes in a US-based commercial carpet industry.

Literature review on SEM

The increasing competition has been compelling the modern organizations to adopt new business practices and new methodologies for continuous improvement (Kannabiran and Bhaumik 2005). The turning point in the development of statistical modeling is undoubtedly, the advent of comprehensive methodologies for SEM and multilevel (regression) modeling. SEMs have been generalized to accommodate different kinds of responses at different levels. Tenenhaus et al. (2005b) presented the partial least squares (PLSs) path modeling with PLSs approach to SEM and discussed its extensions. The study has been compared with estimation of SEM by means of maximum likelihood estimates. Lin et al. (2005) in their work on structural equation model of supply chain quality management and organizational performance used the empirical data collected to identify the factors influencing the supply chain performance. Thus, empirical results presented could be used to improve the management of supply chain networks which further enhances the possibility of extending SEM to other fields. The factors affecting world class manufacturing and its evaluation using SEM done by Eid (2009). The author used the statistical tool, SEM for finding the relationship among variables and for quantification. This quantification thus helped to identify the factors which are influential in manufacturing aspects. Maani et al. (1997) empirically analyzed the quality improvement in manufacturing and its effects in the organization. The study focused on direct and indirect relationships between quality, productivity, and manufacturing performance. The need to empirically test and refine the proposed factors and to explore relationships among the various variables is well explained in their work. Kadipas and Pexioto (1999) extended the study to global manufacturing practices and evaluated the same using SEM. Prajogo (2005) examined the difference between manufacturing and service firms with respect to the implementation of total quality management (TQM) practices, and the relationship of these practices to quality performance.

Research gap

Though, SEM technique has been used by the researchers for certain purposes, the application of SEM technique to model the sustainable manufacturing system enablers and outcomes has not been attempted which formed the research problem. The review of literature indicated that no concrete research has been attempted to develop the structural model of sustainable manufacturing practices which must be practically feasible in industrial scenario. In this context, this study has been conducted.

Theory of SEM

Researchers prefer SEM because it involves the estimation of multiple and interrelated dependence in a single analysis. SEM involves the usage of two types of variables, namely, endogenous variables and exogenous variables. Endogenous variables are comparable to dependent variables, and

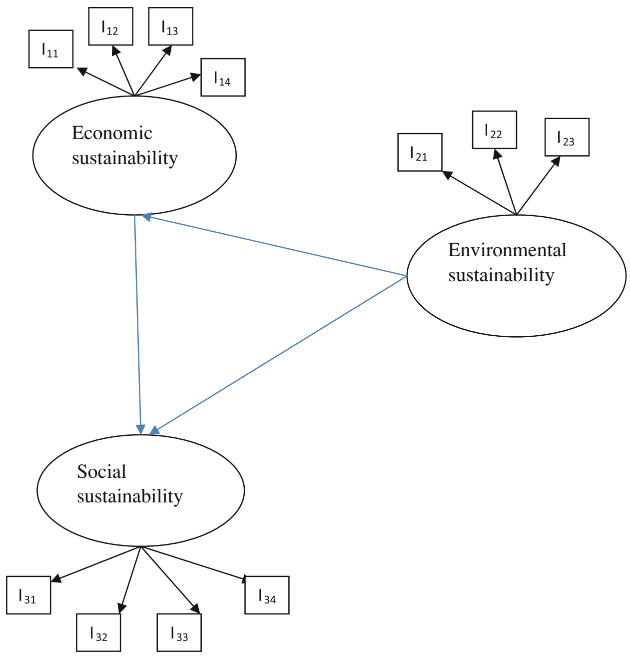

Fig. 1 Model used in SEM

exogenous variables are equivalent to independent variables. SEM is used to analyze the relationship between improvement programs and performance outcomes. Variables used in SEM can be observable or unobservable (Bagozzi and Yi 1988). SEM approaches allow direct testing of hypotheses about unobservable, but at a cost in complexity, and perhaps difficulty in interpreting exactly what the SEM statistics have concluded about each hypothesis. Due to its ability to allow the researcher to focus on the structural level, SEM is considered more flexible than other statistical methods. It is also possible to include variables in an SEM model to test their indirect effects. Such variables are said to mediate the relationships among the variables of main interest in the model.

SEM is also called causal modeling because SEM tests the proposed casual relationships. The conceptual model which has been considered in this study consists of enablers which are subdivided into criteria and attributes as shown in Fig. 1. The main enablers considered in this study are economic sustainability and environmental sustainability, and its relation with social sustainability.

Methodology

This study is focused on the analysis of sustainable manufacturing implementation among the 50 SMEs located in Tamil Nadu, India. The excerpt of the questionnaire used in the research study is shown in Table 1.

SEM was used to test the model with data collected using an email questionnaire. Effective sustainable manufacturing practices have become a potentially valuable way of securing competitive advantage and improving organizational performance since competition is no longer between organizations, but among sustainable manufacturing practicing firms. This research conceptualizes and develops two dimensions of sustainable manufacturing practices which are economic sustainability and environmental sustainability and tests the relationship between social sustainability. In our conceptual model, each unobserved (latent) variable comprises a number of constructs. The economic sustainability consists of four constructs: Financial health (I_{11}), economic performance (I_{12}), potential financial benefits (I_{13}), and trading opportunities (I_{14}). The environmental sustainability consists of air resources (I_{21}), water resources (I_{22}), and mineral and energy resources (I_{23}). The social sustainability consists of four constructs internal human resources (I_{31}), external population (I_{32}), stake holder participation (I_{33}), and macro social performance (I_{34}). For the purpose of study, economic sustainability, environmental sustainability, and social sustainability are considered as the latent variables. The conceptual framework presented in Fig. 2 is drawn from the SEM approach. A conceptual framework was developed incorporating dimensions of sustainable manufacturing.

A 10 point scale has been used to measure each variable. Based on the data and the conceptual model created, the empirical assessment is performed for the model. The modeling of the variables is done with Visual Path Least Square (VPLS) software which is exclusively used for the SEM. In this model, there are three hypotheses which are being tested for validity. The hypotheses include the following.

H1: Environmental sustainability and economic sustainability are significantly correlated.

H2: Environmental sustainability and social sustainability are significantly correlated

H3: Economic sustainability and social sustainability are significantly correlated

Reliability and validity tests

The responses given in the returned filled in questionnaire were converted into data, which were used subsequently for conducting the reliability and validity tests. During the reliability tests, the reliability of the constructs given in the questionnaire was tested using VPLS software. The reliability of the constructs refers to the accuracy with which the constructs repeatedly measure the same phenomenon within permissible variation. The reliability of each construct in the questionnaire was tested using Cronbach's alpha (Cronbach 1951). An alpha score larger than 0.7 is

Table 1 Excerpt of the questionnaire used in the research

Questions (related to the constructs)	Strongly disagree	Disagree	Neutral	Agree to some extent	Strongly agree
1. Is the profitability of the organization high?	2	4	6	8	10
2. Do technological improvements help in achieving sustainability?	2	4	6	8	10
3. Whether global warming affects the products?	2	4	6	8	10
4. Does the release of water effluents and pollutants affect environment?	2	4	6	8	10
5. Adoption of contribution to depletion of non-renewable energy resource?	2	4	6	8	10
6. Are the research and development activities prevailing in the organization?	2	4	6	8	10

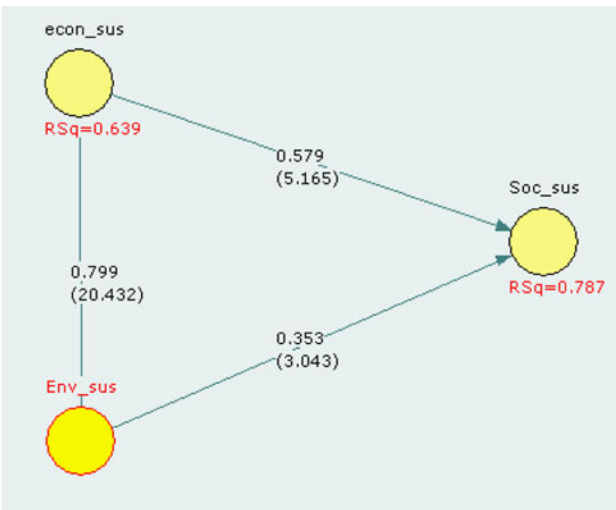

Fig. 2 Visual PLS model

generally acceptable as sufficient accuracy for a construct (Nunnally 1978). Each construct is embodied by the indicators. During this research, the reliability tests were conducted in two stages. In the first stage, five mentioned constructs and their indicators were subjected to reliability tests. First, the correlation of the constructs being computed and is shown in Table 2. Then, the Cronbach's alpha value for all the constructs was computed which is shown in Table 3.

As mentioned earlier, a Cronbach's alpha value more than 0.7 is sufficient to accept the reliability of the constructs. From Table 3, all the constructs show good reliability since the Cronbach's alpha value is greater than 0.7 for all the constructs. Three constructs have AVE values less than 0.5 which shows a lack of convergent validity. According to the stipulated procedure, the process is to be repeated by discarding the indicator with AVE value less than 0.5 (Churchill 1979). To overcome this, purification process is done for the indicators which have loading value less than 0.5 and the model is executed. The re-run results are shown in Table 3. From Table 3, all the constructs have AVE value greater than 0.5 which shows the improvement in convergent validity done by the purification process of the indicators. After deriving reliable constructs by the purification process the constructs were tested for validity using Visual PLS package. The details are shown in Table 4.

For this purpose, the model shown in Fig. 2 was constructed using Visual PLS which is a user-friendly modeling package. The indicators obtained after purification were entered into the model drawn using Visual PLS.

Results

After conducting the reliability and validity tests, the data gathered through the questionnaire based survey were used to test the hypotheses indicated in the literature survey section of this article (Fig. 2). For this purpose, Bootstrap procedure was applied using the Visual PLS package. Bootstrap refers to the selection of samples repeatedly from the collected data with replacements. The mean and variance of the samples thus compiled are compared with the original mean and variance to compute the *t*-statistic, which decides the significance of the hypotheses. After pressing the bootstrap button, the bootstrapping process was carried out by the Visual PLS software. The Visual PLS model is shown in Fig. 2. Figure 2 gives pictorial details about the constructs, hypotheses, and its validity.

The final table which corresponds to the structural model is shown in Table 5. The *t*-value for all the hypotheses in Table 5 is greater than two. A *t*-statistic of more than two leads to the acceptance of the hypothesis. The model with the beta value of the entire sample estimate and *t*-statistic displayed by the Visual PLS is shown in Fig. 2. Besides, the display indicates R^2 value which also

Table 2 Correlation of latent variables

	Economic sustainability	Environmental sustainability	Social sustainability
Economic sustainability	1.000		
Environmental sustainability	0.799	1.000	
Social sustainability	0.861	0.816	1.000

Table 3 Validity of constructs

Construct	Composite reliability	AVE	Cronbach alpha
Economic sustainability	0.962727	0.866000	0.948009
Environmental sustainability	0.845395	0.649875	0.731801
Social sustainability	0.927357	0.761798	0.895473

Table 4 Bootstrap results of the model

Construct	Indicator	Entire sample estimate	Mean of sub samples	Standard error	*t*-Statistic
Economic sustainability	I_{11}	0.2836	0.2833	0.0092	30.9389
	I_{12}	0.2431	0.2435	0.0089	27.2318
	I_{13}	0.2603	0.2602	0.0093	27.9783
	I_{14}	0.2863	0.2849	0.0098	29.0742
Environmental sustainability	I_{21}	0.481	0.4768	0.0384	12.5308
	I_{22}	0.4452	0.4412	0.0303	14.6846
	I_{23}	0.3029	0.305	0.0358	8.4491
Social sustainability	I_{31}	0.3264	0.3247	0.0197	16.5447
	I_{32}	0.2749	0.2744	0.0119	23.1021
	I_{33}	0.2837	0.2825	0.0122	23.16
	I_{34}	0.2587	0.2589	0.0095	27.1893

Table 5 Parameters of structural model

Hypothesis	Entire sample estimate	Mean of sub samples	Standard error	*t*-Statistic
Environmental sustainability → economic sustainability	0.799	0.8036	0.0391	20.4321
Economic sustainability → social sustainability	0.579	0.5803	0.1121	5.1652
Environmental sustainability → social sustainability	0.353	0.352	0.116	3.043

indicates a good deal of influence yielded by economic sustainability and environmental sustainability, and its relation with social sustainability in the Indian society being considered in this research. The results are detailed in Table 5.

The reliability tests show that all the constructs are reliable, since each construct has Cronbach's alpha reliability factor greater than 0.7. The *t*-statistic proves all hypotheses are valid. There exists a strong correlation among the following constructs.

(1) Environmental sustainability and economic sustainability.
(2) Environmental sustainability and social sustainability.
(3) Economic sustainability and social sustainability.

Practical implications

The sustainable manufacturing model has been developed, and the constructs are found to be feasible for SMEs. The hypotheses have been formulated, and the significant correlation between the sustainability enablers has been tested. Thus, the approach analyses the sustainable manufacturing system not only theoretical viewpoint but also from empirical validation.

Conclusions

The contemporary manufacturing organizations are focussing on ensuring clean and green atmosphere by means of reduction of production cost and prevention of environmental problems (Sadiq and Khan 2006). Green system focuses on maximization of resources efficiency for the production of sustained products (Bovea and Wang 2007). This study analyses the sustainable manufacturing not only from theoretical view point but also from empirical validation which is aimed at determining the compatibility of sustainable manufacturing in real time industrial scenario. This study is focused on the analysis of sustainable manufacturing implementation among the 50 SMEs located in Tamil Nadu, India. Based on literature review, a conceptual model has been proposed which has been tested in a small sample of SMEs. The sustainable manufacturing is identified as a global manufacturing model with full fledged integration of

(1) Environmental sustainability and economic sustainability.
(2) Environmental sustainability and social sustainability.
(3) Economic sustainability and social sustainability.

The positive and significant influence of the environment on implementation of sustainable manufacturing practices was tested. Environmental, economic, and social sustainability have been identified as important drivers for sustainable manufacturing. This study utilizes a systematic approach to the analysis of sustainable manufacturing system, considering the sustainable practices or enablers in an integrated manner. This approach is essential because most literature on sustainable manufacturing deals with sustainability strategy or techniques in an isolated manner. This research study fills the literature gap by analyzing not only from theoretical viewpoint but also from empirical viewpoint, testing the suitability of sustainable manufacturing in real time environment.

References

Azzone G, Noci G (1996) Measuring the environmental performance of new products: an integrated approach. Int J Prod Res 34(11):3055–3078

Bagozzi R, Yi Y (1988) On the evaluation of structural equation models. J Acad Mark Sci 16(1):74–94

Bevilacqua M, Ciarapica FE, Giacchetta G (2007) Development of a sustainable product lifecycle in manufacturing firms: a case study. Int J Prod Res 45(18–19):4073–4098

Bovea MD, Wang B (2007) Redesign methodology for developing environmentally conscious products. Int J Prod Res 45(18–19):4057–4072

Churchill GA (1979) A paradigm for developing better measures of marketing constructs. J Mark Stud 16:12–27

Cronbach LJ (1951) Coefficient alpha and internal structure of tests. Psychometrika 16:297–334

Detty RB, Yingling JC (2000) Quantifying benefits of conversion to lean manufacturing with discrete event simulation: a case study. Int J Prod Res 38(2):429–445

Eid R (2009) Factors affecting success of world class manufacturing implementation in less developed countries. J Manuf Technol Manag 20:989–1008

Gungor A, Gupta SM (1999) Issues in environmentally conscious manufacturing and product recovery: a survey. Comput Ind Eng 36:811–853

Ijomah WL (2007) Development of robust design-for-remanufacturing guidelines to further the aims of sustainable development. Int J Prod Res 45(18–19):4513–4536

Kadipas N, Pexioto MB (1999) Global manufacturing practices: an empirical evaluation. Ind Manag Data Syst 99(3):101–108

Kaebernick H, Kara S, Sun M (2003) Sustainable product development and manufacturing by considering environmental requirements. Robot Comput Integr Manuf 19:461–468

Kannabiran G, Bhaumik S (2005) Corporate turnaround through effective supply chain management: the case of a leading jewellery manufacturer in India'. Supply Chain Manag Int J 10:340–348

Lin C, Chow WS, Madu CN, Kueic CH, Yua PP (2005) A structural equation model of supply chain quality management and organizational performance. Int J Prod Econ 96:355–365

Liping Y, Yuqing C, Yuntao P, Yishan W (2009) Research on the evaluation of academic journals based on structural equation modeling. J Informetr 3:304–311

Maani KE, Putterill MS, Sluti DG (1997) Empirical analysis of quality improvement in manufacturing. Int J Qual Reliab Manag 11(7):19–37

Nagel MH, Tomiyama T (2004) Intelligent sustainable manufacturing systems, management of the linkage between sustainability and intelligence, an overview. In: IEEE international conference on systems, man and cybernetics, the Netherlands, pp 4183–4188

Nunnally JC (1978) Psychometric theory. McCraw-Hill, New York

Prajogo DI (2005) The comparative analysis of TQM practices and quality performance between Manufacturing and service firms manufacturing and service firms. Int J Serv Ind Manag 16(3):217–228

Rusinko CA (2007) Green manufacturing: an evaluation of environmentally sustainable manufacturing practices and their impact on competitive outcomes. IEEE Trans Eng Manag 54(3):445–454

Sadiq R, Khan FI (2006) An integrated approach for risk-based life cycle assessment and multi-criteria decision-making: selection, design and evaluation of cleaner and greener processes. Bus Process Manag J 12(6):770–792

Senthilkumaran D, Ong SK, Tan BH, Nee AYC (2001) Environmental life cycle cost analysis of products. Environ Manag Health 12(3):260–276

Singh RK, Kumar S, Choudhury AK, Tiwari MK (2006) Lean tool selection in a die casting unit: a fuzzy-based decision support heuristic. Int J Prod Res 44(7):1399–1429

Tenenhaus M, Vinzi V, Chatelin YM, Lauro C (2005a) PLS path modeling. Comput Stat Data Anal 48:159–208

Tenenhaus M, Vinzi VE, Chatelin YM, Lauro C (2005b) PLS path modeling. Comput Stat Data Anal 16:297–334