Green implementation of Lean Six Sigma projects in the manufacturing sector

ABSTRACT

Purpose - Historically, Lean Six Sigma (LSS) implementation has demonstrated a great deal of enhancement to process efficiency, profitability and customer satisfaction. The emerging market pressure for developing better quality, cheaper and greener products invokes a change of view in LSS economical effectiveness. The purpose of this study is to identify under which condition the final output of LSS projects with traditional strategic benefits are more environmental friendly.

Design/methodology/approach – To investigate the choice of different types of LSS projects, the environmental impact under different conditions and comparison of those conditions, we developed an analytical mathematical model and analysed four different propositions.

Findings - The final price and production volume were recommended as mediating factors to leverage a LSS project to achieve greener, customised and finance–oriented outputs.

Research limitations/implications – This research contributes to existing LSS research and knowledge development via promoting different perspective of LSS and environmental sustainability integration.

Practical implications - This study further enables managers to identify the cut-off point in relation to the production volume and finished prices to leverage the expected financial outputs and environmental impact of the LSS project. This would potentially promote a green LSS project in both implementation and output, alongside its traditional values.

Originality/value - This study uses a modelling approach to identify the conditions under which the actual methodology of LSS project could be green via less energy consumption with a consideration of expected LSS values and outcomes.

Key words – Lean Six Sigma, Green Manufacturing, Environmental Sustainability, Energy Consumption, Mathematical Modelling

1. Introduction

The immense competition in global manufacturing and continuous emerging demand from consumers for better quality and cheaper products and services have been the major factor in competitive manufacturing. For this reason, more and more companies search for management methodologies that allow them to improve their products and services, enhance their processes, decrease costs and improve profitability and customer satisfaction (Tenera and Pinto, 2014; and Jou, *et al*., 2010). Various quality improvement initiatives have been deployed in manufacturing organisations in the global scale within the last few decades, which enhances organisational performance and meets ever-growing customer needs. However, Habidin *et al*.

(2016) reports that over 70% of these organisations failed due to lack of a continuous strategic and holistic control system. Meanwhile, the ever-growing customer needs require the use of effective improvement tools for optimisation and better decision-making (Sharma and Sharma, 2014). This demand inevitably increases the use of natural resources and energy, which are considered as the major sustainability threats.

The existing environmental changes and deficiency of energy resources are also two crucial challenges that the manufacturing sector faces (Shrivastava and Shrivastava, 2017; Mansouri, *et al*., 2016; and Hong, *et al*., 2016). As reported by Mansouri *et al*. (2016), significant energy use by manufacturers contributes to over 36% of global CO_2 emission, which have obliged the manufacturing sector to be proactively engaged with reduction of their environmental impact. Increasingly, stakeholders including consumers have been asking manufacturers to be more environmentally responsible with respect to their products and processes (Luo, *et al*., 2016; and Rusinko, 2007). In order to respond to growing environmental regulations and more customer demand for greener products, the "Green paradigm" has been considered as important as traditional domains such as profitability, quality, efficiency and customer satisfaction. Therefore, the organisation's performance is measured based on perspectives of both customer and environment (Garza-Reyes, *et al*., 2017). Difficulties in planning, measuring and deploying sustainability and their crucial role in manufacturing decision making also necessitates the systematic integration of sustainability with business excellence models (Rocha-Lona, *et al*., 2015). The notion of sustainability and reducing environmental impacts in manufacturing processes is no longer an option, but a business imperative for gaining a competitive advantage.

Both scholars and business managers have extensively noted Lean Six Sigma (LSS), which is an integrated, systematic and structured business excellence methodology in the manufacturing sector, and its benefits have been documented (Habidi, *et al*., 2016; and Khawar, *et al*., 2016). However, for more strategic benefits, manufacturing organisations need to consider the synergies and conflicts of these two crucial competitive advantage initiatives. Green LSS was proposed to have strategic importance in manufacturing towards efficiency, optimisation and achieving sustainability (Kumar, *et al*., 2016). Despite a great deal of successful integration between LSS and sustainability, barriers are bound to be encountered (Yadav et al, 2018; Cherrafi, *et al*., 2017; Kumar, *et al*., 2016; Dues, *et al*., 2013; and Garza-Reyes, *et al*., 2014). This conflict is due to the LSS objectives of meeting customer desire and demand for quality and durability, which may use non-sustainable practices and material

(Cherrafi, *et al*., 2016). How to align the objectives of LSS and sustainability in manufacturing so that the manufacturer does not need to put extra investment to achieve sustainability is an untapped problem (Cherrafi, *et al*., 2016). This research aims to fill this gap by developing a structured model to identify the conditions under which a LSS practice with less energy use in manufacturing processes. This paper contributes to the literature in the following ways: i) a hybrid framework was developed for LSS implementation for the green manufacturer with less energy use; ii) an analytical model was developed to analyse the manufacturer's decisions under different LSS projects; iii) managerial insights have been derived from the analysis of the models, we particularly identified the condition under which the final output of LSS projects with traditional strategic benefits is greener.

The remainder of the paper is organised as follows. The literature review in Section 2 mainly concentrates on "Green Manufacturing (GM)" and LSS with their drivers, benefits and challenges. Section 3 develops the conceptual model on LSS implementation for the green manufacturer. Section 4 proposes the mathematical model, which will demonstrate the linkage of LSS projects to the market performance. This will formulate the decision-making problem to identify under which conditions LSS is green. The analysis is conducted in Section 5 and insights are derived. Section 6 concludes the paper.

2. Literature review

This research is related to two strands of literature: one is green manufacturing and the other is LSS in the manufacturing sector.

2.1. Green Manufacturing

According to Garg *et al*. (2015), the manufacturing sector has been accounted for almost one-half of the world's total energy use that has been doubled over the past 60 years. Manufacturers are under tremendous pressure to be competitive through more productivity, increased awareness of environmental responsibilities and meeting growing consumer demand for greener products. Green Manufacturing (GM) is the prominent notion of sustainable manufacturing, which is recognised with concepts such as energy conservation, greener materials and products, waste reduction, emission control and planet protection. Despite challenges over defining GM, it encompasses all factors associated with environmental concerns in manufacturing by continuously integrating eco-friendly industrial processesand products (Chuang and Yang, 2014). Beske *et al*. (2014) stress the essence of sustainable supply chain management and dynamic capabilities for manufacturers via economic, social and environmental sustainability to meet ever-growing and multi-dimensional customer demands. Shrivastava and Shrivastava (2017) defined GM as a method for manufacturing that minimises waste and pollution for all industries. They introduced the GM as a modern concept focusing on green energy, products and processes. In a separate study, Chuang and Yang (2014) recommended proportion of non-toxic materials, compliance with eco-ordinances, proportion of biodegradable materials, environmental pollution per product and extent of process pollution as key success factors of the GM.

The growing regulatory policies manifested in organisational vision and missions that have created unprecedented challenges for manufacturers, especially in relation to meeting consumer demand for greener products (Hitchcock, 2012) and the implied costs (Paulraj and De Jong, 2011). The existing conflict of global sourcing and green purchasing has given this challenge a global label to form a green supply chain with combined economic and ecological advantages (Xie and Breen, 2012; and Kumar, *et al*., 2011). The current research findings revealed that many manufacturers attempt to disclose their environmental performance to obtain a better market response from prices and emissions – sensitive demand (Luo, *et al*., 2016). Through their systematic analysis, Sueyoshi and Got (2010) previously proved a mutual influence between operational and environmental performance in a dynamic interaction to gain financial benefits for larger manufacturers. Eco-efficiency strategies of manufacturing gained considerable attention via meeting both environmental and economic demands by manufacturers and their customers. For instance, Wang *et al*. (2013) investigated the optimal material flow allocation and network design to reduce carbon emissions and increase product value in the manufacturing sector.

Mansouri *et al*. (2016) have proposed energy consumption in manufacturing as a multifaceted issue related to a conflict between machining parameters and operational scheduling, such as machine set up time at the service level. The majority of scholars who work on research in GM focused on the product and process levels, which highlight the waste reduction strategy (Farias et al, 2019; and Deif, 2011). Notwithstanding, Lu *et al*. (2015) signified another side of the GM with an alarming conflict between some common manufacturing strategies and greenness. They argued that Vendor Inventory Management (VIM), as an integrated manufacturing strategy to meet customer demand, would hinder a GM by promoting more carbon footprint. Luo *et al*. (2016) defined low carbon manufacturing as the manufacturing process that produces low carbon emission intensity through the efficient and effective use of energy and resources during the process to meet regulatory policies. According to Hong *et al*. (2016), in a study about green production planning, a credible emission control strategy to make a good balance between emissions and costs to comply with new policies was recommended as an essential component of the business success.

Waste reduction is recognised as another important practice in GM that entails a great deal of synergy with lean manufacturing. Manufacturers are thought to be one of the biggest producers of waste. Transparency of demand information, quality management and process control have been among major propositions to control environmental waste in manufacturing, according to Mena *et al*. (2014). This relates to enhancing demand visibility to meet supply and minimising the special causes of defects in the process that will result in excessive waste. The elimination of waste as a predominant strategy for manufacturers at all levels has made the greenness compatible with lean manufacturing in many aspects (Farias et al, 2019; and Garza-Reyes, *et al*., 2017). Cost reduction as the result of waste minimisation predominantly is the major benefit as the result of the synergy between lean and GM.

Despite clear financial benefits of the GM, its real impact on organisational competitive outcomes is somewhat inconclusive (Rusinko, 2007). With an extensive empirical investigation, it was reported by Digalwar et al (2013) that companies are facing challenges to assess the performance of green manufacturing. In a significant disclosure, Deif (2011) identified a requirement for a more holistic system model to assess GM metrics in planning, design, production, and control levels to minimise the confusion arisen from failing to describe greenness in a multi-dimensional strategic perspective of manufacturing. Shrivastava and Shrivastava (2017) also emphasised a complete and holistic approach to the green product design with the aid of green processes. Rajala *et al*. (2016) revealed that incorporated GM in business strategy alongside profound managerial and leadership commitment is required to create a re-configured business ecosystem and a re-invented business model. They believe that this will mandate a greener mind-set and roadmap for radical proactive alterations in relevant manufacturing activities. Despite recommendation of twelve performance measurement of green manufacturing by Digalwar et al (2013) via the factor analysis, they failed to consider the project management and project life cycle assessment of environmental impact.

2.2. Lean Six Sigma in the manufacturing sector

Lean Six Sigma (LSS) is a business excellence tool with a significant focus on reducing the opportunity for variation and waste. LSS was defined by Snee (2010) as “a business strategy and methodology that increases process performance resulting in enhanced customer satisfaction and bottom line result”. LSS has evolved through the combination of Lean and Six Sigma both being recognised as leading Total Quality Management (TQM) tools for performance improvement in organisations with a proper infrastructure that are built on leadership and change of culture (Shamsuzzamana, et al, 2018; Vijaya Sunder et al, 2018; Shokri, *et al*., 2016; Habidin, *et al*., 2016; Dora and Gellynck, 2015; Assarlind, *et al*., 2013; Wang and Chen, 2012; Choi, *et al*., 2012; Hilton and Sohal, 2012; Atmaca and Girenes, 2013). It is recognised as one of the most effective and disciplined top-down business transformation initiatives for improving quality and reducing waste in both the manufacturing and service sectors (Gijo et al, 2018; Antony et al, 2016; Kanpp, 2015; Isa and Usmen, 2015; Bhat, *et al*., 2014; Algasem, *et al*., 2014; and Biranvand and Khasseh, 2013).

LSS is formed with the balanced integration of Six Sigma as a systematic and rigorous tool to uncover and reduce defect and variation in breakthrough projects and Lean Management, with continuous incremental reduction of waste, environmental and economic sustainability, increasing the speed of the operation and delivering the value (Muganyi et al, 2019; Gijo et al, 2018; Tortorella et al, 2018; De Freitas and Gomes Costa, 2017; Marques and Matthe, 2017; Thomas, *et al*., 2016; Bamford, *et al*., 2015; Piercy and Rich, 2015; Choi, *et al*., 2012; Hilton and Sohal, 2012; and Manville, *et al*., 2012). At an operational level within the manufacturing sector, the LSS model aims to clarify the process of identifying opportunities, as well as reduce variability and improve the quality of the manufacturing process (Muganyi et al, 2019; Holmes, *et al*., 2015). By utilising the LSS five-phased systematic methodology of DMAIC (Define, Measure, Analysis, Improve, Control), integrated with five general phases of project management (initiation, planning, execution, control and closing), manufacturers can tackle their own specific problems (Walter and Paladini, 2019; Sreedharan and Sunder, 2018; Marques and Matthe, 2017; Tenera and Pinto, 2014; and Gupta, *et al*., 2012). One of the most crucial steps of the LSS project is to identify the customer demand or voice of the customer and translate it to a prioritised Critical to Quality (CTQ) metric (Tenera and Pinto, 2014 and Lighter, 2014) that serves as the outcome variable. Despite longitudinal research with acknowledgement of the synergy between Lean and Six Sigma as combined initiatives to establish quality (Singh and Rathi, 2019; and Habidin, *et al*., 2016), there is a conflicting view to argue Lean and Six Sigma as two non-compatible management initiatives (Pepper and

Spedding, 2010). The previous unsuccessful experience of implementing LSS in manufacturing criticised it as being slow, bureaucratic and exclusive (Geier, 2011).

Any LSS project success depends on many organisational and leadership aspects as essential ingredients. Formal mechanisms of management involvement, cultural transformation, appropriate project selection, project review, goal setting, training, understanding the methodology and tools, product/process design and improvement, and linking LSS to business strategy and customers have been recommended as major critical success factors (CSFs) of LSS implementation (Walter and Paladini, 2019; Tlapa, *et al*., 2016; Khawar, *et al*., 2016; Aldowaisan, *et al*., 2015; Abu Bakar et al, 2015; Antony, 2014; and Sabry, 2014). Geier (2011) introduced CSFs of LSS in cultural perspective for manufacturers. He emphasised on a team reinvigoration with employee's ownership and simpler flexible use of LSS to guarantee success.

Manufacturers have been obliged to incorporate quality and business excellence tools such as LSS in their strategic and operational level to meet competitiveness via increased customer satisfaction, financial enhancement, improved product quality and reduced cost. Higher influence of product quality on the customer for New Product Development (NPD) and innovation has justified an application of traditional design for LSS in the manufacturing sector (Muganyi et al, 2019; and Alvarez, 2015). In fact, Design for Six Sigma (DFSS) was introduced as a proactive tool to develop newly designed or re-designed products and services to meet customer demand. DFSS is defined as a systematic management technique that optimises products, services and procedure design through common define-measure-analysis-design-verify methodology (Thakore, *et al*., 2014; and Jou, *et al*., 2010).

Using statistical and reliable data and analysis tools and techniques within systematic roadmaps, LSS implementation in manufacturing facilitates breakthrough results with enhanced quality of products and services (Gijo et al, 2018; Zhang et al, 2016; Thomas, *et al*., 2016; and Sharma and Sharma, 2014). Adina-Petruta and Roxana (2014) presented key strategic benefits of LSS as sustainable improvement with high productivity level and accelerated results, while many scholars have presented operational benefits of LSS as reduced process variability, improved product quality, waste and defect reduction (Singh and Rathi 2019; Thomas, *et al*., 2016; Tlapa, *et al*., 2016; Chaneski, 2016; Dragulanescu and Popescu, 2015). Despite extensive evidence for benefits of LSS, many scholars have identified key barriers for its implementation in the manufacturing sector such as; resistance to change, expenses, lack of resources, poor project selection, the wrong perception of LSS as a set of tools and techniques, inefficient use of techniques and resources, misalignment between project goals and manufacturing strategy, ineffective project management and poor communication (Singh and Rathi 2019; Yadav et al, 2018; Albliwi, *et al*., 2014; and Ismail, *et al*., 2014).

Although scholars have presented major strategic and operational benefits of LSS, a few studies have investigated what leads to LSS project performance (Arumugam, *et al*., 2016). It has also been inconclusive among scholars to what metrics need to be reviewed. Whilst, many researchers analysed the LSS behavioural impact in relation to project deliverables such as goal setting, project success rate and knowledge creation, other mediators also need consideration (Arumugam, *et al*., 2016). For instance, the understanding of inter-relationship between these technical factors and social and environmental factors need to be contemplated in the future LSS projects. Therefore, we decided to investigate the environmental impact of LSS projects against a traditional LSS approach to promote GM.

2.3.LSS implementation for a green manufacturer

There has recently been a growing number of research and LSS projects in relation to the benefits of LSS to make manufacturers greener (Kaswan and Rathi; 2019; Seedharan et al, 2018; Garza-Reyes, *et al*., 2017 Worley and Doolen, 2015; and Banawi and Bilec, 2014). In one of the most recent studies, the more sustainable LSS frameworks for the manufacturers have been recommended as future agenda (Singh and Rathi 2019). In another recent study and through their green LSS enablers framework, Kaswan and Rathi (2019) revealed that organizational readiness for Green LSS together with competence for green product and process have been found as the most prominent driving enablers of Green LSS. Despite a clear synergy between lean and green initiatives, product and process design and manufacturing strategies may result in a disconnection between these two initiatives (Hartine and Ciptomulyono, 2015). This would promote integrating these initiatives with Six Sigma to create a hybrid framework that covers the process, product and plant under one roof. Sagnak and Kazancoglu (2016) revealed that Six Sigma integration towards lean and green practices will facilitate a more rigorous and scientific approach to variation and waste reduction. However, this mainly represents the traditional LSS that is predominantly only quality-oriented CTQ. Thomas *et al*. (2016) have previously substantiated this argument that traditional LSS aims for quality and business enhancement in the outcome. There is an ever-growing demand by policymakers and end consumers for greener and better quality products and processes with significant reduced energy consumption (Kumar, *et al*., 2016; Shriavastava and Shriavastava, 2016; Luo, *et al*., 2016; Mansouri, *et al*., 2016; Garg, *et al*., 2015; and Rusinko, 2007). Despite greater number of research studies on the impact of LSS on greener manufacturing in the point of view of product, design and even supply chain (Kaswan and Rathi, 2019; Seedharan et al, 2018; Chugani el al, 2017; Garza-Reyes, et al., 2017; Worley and Doolen, 2015), there is not enough focus on conflicting factors in the point of view of energy consumption in actual LSS project life cycle. This obliges researchers and managers in the manufacturing sector to enforce more consideration into the environmental impact of the actual LSS projects. This means, in addition to benefits of LSS for green manufacturing, the barriers or conflicts to make the LSS project and methodology greener, also need attention.

The systematic roadmap of DMAIC for continuous problem solving and enhancement with different stages and extensive use of resources may create an environmental conflict as sustainability detrimental impact (Sreedharan and Sunder, 2018; Marques and Matthe, 2017; Kumar, *et al*., 2016; and Dragulanescu and Popescu, 2015). This is predominantly associated with energy consumption to meet the highest level of quality and customer demand as key LSS goals. In its best scenario, LSS increases the energy used to meet the stretched and challenging goals (Arumugam, *et al*., 2016). Energy consumption has always been a key environmental challenge in manufacturing (Mansouri, *et al*., 2016 and Garg, *et al*., 2015). Hence, to produce greener products with greener processes, any agent of the LSS methodology that contributes to increased energy used such as the “Define” and “Improve” stages needs to be re-examined. The greater use of resources (e.g. water, electricity, material) and machinery for continuous data collection and various test and error applications for optimum improvement solution in both “Define” and “Improve” made these two stages more energy consuming (Seedharan et al, 2018; Chugani el al, 2017). The possibility of using environmentally harmful or unsustainable material as part of solutions for better performance would also add to the environmental impact (Cherrafi, et al, 2016). This encourages more careful planning, goal setting, tool utilisation and improvement practices. For example, Khawar *et al*. (2016) in their LSS action research for Steel manufacturing recommended a higher level of temperature to reduce the rejection and scrap rate, and therefore waste reduction and improved optimisation after the systematic and rigorous “Design of Experiment” part of LSS. However, there is a conflict between less energy use and CO_2 emissions with applying higher temperature in principle.

Tenera and Pinto (2014) introduced LSS project execution and closing phases as two major sources of project inefficiency that would potentially have the environmental impact associated with excessive resources and energy used. In their more detailed and focused research about barriers in green LSS product development process, Kumar *et al*. (2016) revealed various conflicting elements of this integration. We present those conflicting elements with significant environmental and energy impact. They include; poor utilisation of infrastructure, poor visual control and management, using non-green material and operations in "Improve" stage, non-green material handling and logistics, inappropriate identification of goals and DMAIC strategies for greener manufacturing, excessive energy use in the "Improve" stage, lack of funding, lack of suppliers willing to provide greener material and consultation, and lack of top management commitment to reduce environmental impact of LSS methodology. Therefore, it was decided to investigate under which condition CTQ metric is green with less energy used in LSS projects. Figure 1 depicts the hybrid framework that was developed by us to indicate two different routes of "Traditional LSS" with only quality-oriented CTQ outcome and "Green LSS", with quality and green- oriented CTQ. The latter reflects the energy use as one of the key environmental impact indicators alongside traditional quality and profitability metrics.

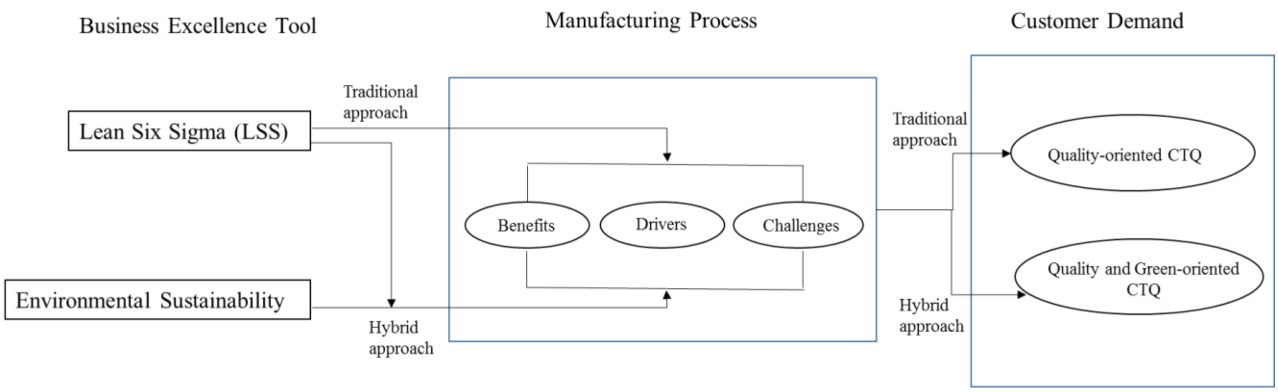

Figure 1 – Hybrid framework of green and traditional LSS approaches to manufacturing processes

In congruence with the analysis revealed by Kumar *et al*. (2016), Cherrafi *et al*. (2016) have acknowledged the need for more a holistic, hybrid and integrated model to facilitate understanding, and investigate the negative and conflicting effect of LSS implementation to environmental sustainability as a clear research and managerial gap. The next section of this paper is dedicated to introducing a mathematical model to propose the conditions that LSS projects could have a less negative environmental impact.

3. Mathematical Model Development

The proposed problem under the LSS project selection framework was studied (Kalashnikov, *et al*., 2017). By investigating the choice of different types of LSS projects, we study the environmental impact and identify the conditions. Specifically, we assume that a manufacturer produces one product with unit cost c_m. The manufacturer makes a decision on the price. Consumers are heterogeneous on the valuation of the product. Assuming that the valuation θ is uniformly distributed between 0 and 1, that is, $\theta \sim U(0,1)$. The market size is normalised to 1. Under this setting, the demand is $Q = 1 - p$, where p is the unit price for the product. This demand framework is commonly used in the literature (Atasu, *et al*., 2008). The unit environmental impact of the product is E_0, which includes all possible environmental impact, for example, production, transportation etc (King and Lenox, 2001). We use subscript $i, i = 1,2,3$ to denote the different projects. The detailed notations are defined in Table 1.

Table 1 near here

The manufacturer wants to implement a LSS project with a budget which can only be used in one LSS project: quality improvement, revenue-enhancing, cost-saving, or environment. Improvement of the first three types were proposed by Hariharan (2013). Because the quality improvement and revenue-enhancing projects are customer-oriented, we combine the two as a customer-oriented project. For the cost-saving projects, due to their process improvement nature, we rename it as process-oriented projects. Besides the two broad categories, we add another environment-oriented project to include the environmental initiatives using LSS. Therefore, the three types of LSS projects, which have different impacts on different aspects are investigated:

(1) Customer-oriented project - that is LSS projects aim to improve customer satisfaction, which can increase the valuation of the product with a coefficient $\alpha \geq 1$.
(2) Process-oriented project - This type of project has no direct impact on the consumer, but on the unit cost. By implementing the project, the unit cost will be reduced to βc_M, where $0 < \beta < 1$.
(3) Environment-oriented project - This type of project has no direct impact on the consumer and process, but rather reduces the unit environmental impact. By implementing such project, the unit environmental impact will be reduced to γE_0,

where $0 < \gamma < 1$. However, the green image of this project will increase the valuation of the product from green consumers who account for $\delta, 0 < \delta < 1$ of the total market, and the valuation increase is $\varepsilon \geq 1$ (Atasu, *et al.*, 2008).

The above modelling setup has been thoroughly checked by the researchers and field experts. The modelling assumptions are all widely used in the literature. Therefore, the face validity and internal validity can be guaranteed (Ramos, *et al.*, 2015). The following results will be derived based on the above modelling framework.

The objective of the manufacturer is to maximise the total profit.

(1) Benchmark model:

The manufacturer's problem is

$$max_{p_1} \Pi_1 = (p_1 - c_m)Q_1 \quad (1)$$

According to the first order condition (FOC) (equating the first order derivative to zero and solve the equation), we can easily get:

$$p_1^* = \frac{1+c_m}{2}, Q_1^* = \frac{1-c_m}{2}, \Pi_1^* = \left(\frac{1-c_m}{2}\right)^2.$$

(2) Customer-oriented project:

Under this case, the demand is: $Q_2 = 1 - \frac{p_2}{\alpha}$

The manufacturer's problem is:

$$max_{p_2} \Pi_2 = (p_2 - c_m)Q_2 \quad (2)$$

According to the first order condition (FOC), we can easily get:

$$p_2^* = \frac{\alpha+c_m}{2}, Q_2^* = \frac{\alpha-c_m}{2\alpha}, \Pi_2^* = \frac{(\alpha-c_m)^2}{4\alpha}$$

(3) Process-oriented project:

Under this case, the demand stays the same.

The manufacturer's problem is

$$max_{p_3} \Pi_3 = (p_3 - \beta c_m)Q_3 \quad (3)$$

The first order condition yields the following results:

$$p_3^* = \frac{1+\beta c_m}{2}, Q_3^* = \frac{1-\beta c_m}{2}, \Pi_3^* = \left(\frac{1-\beta c_m}{2}\right)^2$$

(4) Environment-oriented project

Under this case, a fraction δ of consumers is willing to pay a premium for the product. The demand becomes:

$$Q = \delta\left(1 - \frac{p}{\varepsilon}\right) + (1-\delta)(1-p) = 1 - (1 - \delta + \frac{\delta}{\varepsilon})p$$

The manufacturer's problem is:

$$max_{p_4}\Pi_4 = (p_4 - c_m)Q_4 = (p_4 - c_m)[1 - (1 - \delta + \frac{\delta}{\varepsilon})p_4] \quad (4)$$

According to FOC, we have:

$$p_4^* = \frac{1 + c_m(1-\delta+\frac{\delta}{\varepsilon})}{2(1-\delta+\frac{\delta}{\varepsilon})},\ Q_4^* = \frac{1 - c_m(1-\delta+\frac{\delta}{\varepsilon})}{2},\ \Pi_4^* = \frac{(1-c_m\left(1-\delta+\frac{\delta}{\varepsilon}\right))^2}{4(1-\delta+\frac{\delta}{\varepsilon})}$$

4. Analysis

From the optimal profits under different projects, it can be seen that the company profits under LSS projects are all greater than that without LSS projects. Here, of course, we do not consider the cost of LSS projects. This makes sense if the company has already done several LSS projects, so that the training costs are neglectable.

4.1. The environmental impact of LSS projects

Now, we look at the environmental impact of the different LSS projects.

Proposition 1: a) The product quantity under LSS projects is bigger than that without LSS projects and so is the profit; b) The environmental impact of customer-oriented and process-oriented projects is always greater than that without LSS projects. c) For an environmental-oriented project, when $\delta \leq \frac{(1-\gamma)\varepsilon(1-c_m)}{\gamma(\varepsilon-1)c_m}$, the total environmental impact is lower than that without LSS projects, otherwise, it is bad for the environment.

The first result is not surprise. They have been well documented that LSS projects have benefits for profitability (Adina-Petruta and Roxana, 2014). The environmental impact of LSS projects is not well discussed in traditional LSS literature. The second result shows that due to the sales volume implications of process improvement and service improvement, traditional LSS project may be bad for environment. The third result is quite interesting; although the purpose of the project is to reduce the energy consumption, the result may turn out the opposite. It means only if the proportion of green consumers is small enough; the environment-oriented LSS project is good for the environment. This is because if the green consumer size is large, this kind of project will stimulate more green consumers to buy the product that causes overconsumption, which in turn increases energy consumption that is bad for the environment. This is the Lean Six Sigma version of Jevons' paradox – technological efficiency gains actually increased the overall consumption of coal, iron, and other resources, rather than "saving them" (Alcott, 2005). Similarly, in environment-oriented LSS, although the purpose of the project is to improve the energy efficiency of the product, the total consumption may increase. This 'rebound effect' may hurt the environment.

4.2. Comparison between different LSS projects

In this section, the different LSS projects are compared. Because of the different parameters in different LSS projects, we cannot compare them directly. Alternatively, we let the total profits equal and see the optimal product quantity and the corresponding environmental impact.

(1) Customer-oriented project vs. Process-oriented project

Initially, the customer-oriented project and process-oriented project are looked at. We have the following finding:

Proposition 2*:* Under the condition of $\Pi_2^* = \Pi_3^*$, we have $Q_3^* > Q_2^*$, $p_3^* < p_2^*$.

From Proposition 2, it can be seen that to produce the same profit, the process-oriented project tends to produce more products. This makes sense because, for process improvement projects, the aim is to reduce cost, which in turn sells products at lower prices resulting in a higher sales volume. Because of this, to make the same profit, process improvement project needs to sell more products, which in turn causes more impact on the environment. Due to the inability of a process-oriented project to increase the consumers' willingness to pay, the company can only use low prices to attract customers. This is corresponding to the everyday-low-price strategy. Process improvement is the key to compete in the market from the internal process improvement perspective. However, for this type of projects, higher sales quantity is important to be profitable, which may not be good from the environment perspective.

(2) Customer-oriented project vs. Environment-oriented project

Using a similar analysis process, we have the following result:

Proposition 3: Under the condition of $\Pi_2^* = \Pi_4^*$, we have $Q_2^* = Q_4^*$, $p_2^* = p_4^*$.

Proposition 3 shows that to achieve the same profit, the customer-oriented project has the same product quantity with the environment-oriented project. However, regarding the environment, because the product quantities are the same, the environment-oriented project could achieve a lower environmental impact. This result makes sense because both LSS projects are focusing on the customer side. Although the two types of project are different, they have a similar impact on the customer demand. Therefore, using the same quantity, both projects can achieve the same profit. However, because the customer-oriented project does not impact the unit environment of the product, the customer-oriented project may produce more harm to the environment compared to the environment-oriented project.

(3) Process-oriented project vs. environment-oriented project

Using a similar process, the process-oriented project and environment-oriented project are compared, and we have the following finding as summarised in Proposition 4:

***Proposition 4**:* Under the condition of $\Pi_3^* = \Pi_4^*$, we have $Q_3^* > Q_4^*$, $p_3^* < p_4^*$.

Proposition 4 means that to achieve the same profit, the process-oriented project needs to produce more products than the environment-oriented project. Meanwhile, because the process-oriented project has a higher unit environmental impact than the environment-oriented project, the total environmental impact under the process-oriented project is higher than that under the environment-oriented project.

Putting the above results together, it can be seen that to achieve the same profit, the process-oriented project needs to produce the highest number of products, while the customer-oriented project and environment-oriented project produce the same quantity, which is lower than the process-oriented project. Meanwhile, regarding the environmental impact, although the environment-oriented project seems the most favourable option, the rebound effect may offset the environment benefit of the LSS project. That means environmental friendly image could be beneficial in terms of both profit and environmental impact under certain conditions. The proof of each proposition is presented as Appendix.

5. Conclusion and managerial implications

We acknowledged that the new era of LSS implementation in manufacturing would promote the essence of greener implementation of LSS in addition to more traditional approaches of LSS such as process enhancement, waste reduction, profitability and customer satisfaction. This creates a re-configured business ecosystem and re-invented business model to mandate a greener mind-set and roadmap for radical proactive alterations in relevant manufacturing activities. Therefore, it was intended to identify the condition under which the final output of LSS projects with traditional strategic benefits are also environmental friendly. Having developed an analytical model to analyse the decisions under different LSS projects, we identified that despite greater efficiency in output, process-oriented LSS projects would not necessarily be green due to potential unit cost reduction and increased volume of product and sales as output. It was also concluded that the production volume and final price for end consumers are recognised as mediating factors to balance the expected result of LSS application and environmental impact of the project. This means that managers need to identify the cut-off point in relation to the production volume and finished prices to leverage the expected financial outputs and environmental impact of the LSS project. In other words, the leveraged volume of finished improved product and finished consumer price should be added to the LSS key success factors to transform more traditional LSS projects to green projects in manufacturing firms.

This analysis is predominantly reliant on an analytical model and encourages scholars and practitioners to conduct some empirical studies in different formats including a case study as future studies. This is to clarify the practical implications of the suggestions provided by our analysis and consider the implementation phase of LSS projects to transform them to a more hybrid approach of greener LSS projects with more efficient, customised and finance-oriented results. Of course, like any other papers, this paper is not without limitations. First, the current model is highly abstracted to characterise the decision in LSS. However, in practice, the decisions and parameters are complex, and incorporating more decisions in the model needs further research. Second, the insights derived from our models could be tested using empirical data and case study. This study has significant contribution towards future LSS research and professional development particularly in relation to hybrid approach of sustainable LSS implementation. Alongside current emerging research development in more hybrid approach of green, lean and six sigma implementation in manufacturing, we recommend consideration of the pricing, volume and energy consumption as indicators as part of added "Sustain" stage to the DMAIC methodology. This can be articulated further through empirical and case study analysis.

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Appendix

Proof of Proposition 1:

a) This result can be easily achieved by comparing the optimal quantity under different scenarios.

b) because the unit environmental impact of customer-oriented and process-oriented projects does not change with the different projects and the total environmental impact depends on the product quantity, therefore, this result can be derived directly from a).

c) For the environment-oriented project, the unit environment impact reduces and the total environmental impact is $Q_4^*\gamma E_0$. We have the following:

$Q_4^*\gamma E_0 - Q_1^* E_0$=$(Q_4^*\gamma - Q_1^*)E_0$

Let the above formula be greater than 0, and solve the inequality we have $\delta \leq \frac{(1-\gamma)\varepsilon(1-c_m)}{\gamma(\varepsilon-1)c_m}$. □

Proof of Proposition 2:

Proof: Equating the profits under the customer-oriented project and process-oriented project, $\Pi_2^* = \Pi_3^*$, we can get the relationship between the parameters. In this case, we look at β as a function of α. Solving the equation with respect to β, we have $\beta = \frac{\sqrt{\alpha}\pm(\alpha-c_m)}{\sqrt{\alpha}c_m}$. Because $0 < \beta < 1$, so we have $\beta^* = \frac{\sqrt{\alpha}-\alpha+c_m}{\sqrt{\alpha}c_m}$. Now, we substitute β^* in the optimal product quantity Q_3^* and minus the product quantity Q_2^*, we have

$Q_3^* - Q_2^* = \frac{(-1+\sqrt{\alpha})(\alpha-c_m)}{2\alpha} > 0.$

Therefore, Q_3^*>Q_2^*.

Because $\Pi_2^* = \Pi_3^*$, and Q_3^*>Q_2^* we have $p_2^* - c_m > p_3^* - \beta c_m$. That is $p_2^* > p_3^* + c_m(1-\beta)$. Therefor, $p_3^* < p_2^*$□

Proof of Proposition 3:

Proof. Solving $\Pi_2^* = \Pi_4^*$ with respect to δ, we have $\delta_1 = \frac{(-1+\alpha)\varepsilon}{\alpha(-1+\varepsilon)}$, $\delta_2 = \frac{(-\alpha+c_m^2)\varepsilon}{(-1+\varepsilon)c_m^2}$. Because $0 <$

$\delta < 1$,

δ_2 should be eliminated. We have $\delta^* = \frac{(-1+\alpha)\varepsilon}{\alpha(-1+\varepsilon)}$. Substitute δ^* in Q_4^* we have $Q_4^* = \frac{\alpha-c_m}{2\alpha}$=$Q_2^*$. It is straightforward that if Q_4^*=Q_2^*, we have $p_2^* = p_4^*$. □

Proof of Proposition 4:

Proof: Solving $\Pi_3^* = \Pi_4^*$ with respect to β, we have $\beta_1 = \frac{1-\sqrt{\frac{(\varepsilon+(\delta(-1+\varepsilon)-\varepsilon)c_m)^2}{(\delta(-1+\varepsilon)-\varepsilon)\varepsilon}}}{c_m}$, $\beta_2 = \frac{1+\sqrt{\frac{(\varepsilon+(\delta(-1+\varepsilon)-\varepsilon)c_m)^2}{(\delta(-1+\varepsilon)-\varepsilon)\varepsilon}}}{c_m}$. Because $0 < \beta < 1$, we only keep β_1, and $\beta^* = \frac{1-\sqrt{\frac{(\varepsilon+(\delta(-1+\varepsilon)-\varepsilon)c_m)^2}{(\delta(-1+\varepsilon)-\varepsilon)\varepsilon}}}{c_m}$.

Substitute β^* in Q_3^*, we have

$Q_3^* = \frac{\varepsilon-(\varepsilon-\delta(\varepsilon-1))c_m}{2\sqrt{(\varepsilon-\delta(\varepsilon-1))\varepsilon}}$.

$Q_4^* = \frac{1-c_m(1-\delta+\frac{\delta}{\varepsilon})}{2} = \frac{\varepsilon-(\varepsilon-\delta(\varepsilon-1))c_m}{2\varepsilon}$.

Because $\frac{\sqrt{(\varepsilon-\delta(\varepsilon-1))\varepsilon}}{\varepsilon} = \sqrt{\frac{(\varepsilon-\delta(\varepsilon-1))}{\varepsilon}}<1$, we have $\sqrt{(\varepsilon-\delta(\varepsilon-1))\varepsilon} < \varepsilon$, which means $Q_3^*>Q_4^*$.

Using the same analysis as Proposition 2, we can show that $p_3^* < p_4^*$ □