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Integrating Sustainability in the Design and Planning of Supply Chains

Kanchan Das
College of Engineering and Technology, East Carolina University
245 Slay Hall, Greenville, NC 27858
Email: dask@ecu.edu (*Corresponding Author*)

Amit Mitra
Harbert College of Business, Auburn University
419, Lowder Business Building, Auburn, AL 36849-5266
Email: mitraam@auburn.edu

ABSTRACT

This research integrates factors and practices relevant to environmental and economic sustainability and, thereby, encapsulates social responsibility in supply chain (SC) design and planning to enhance its overall performance. Such factors and practices are included in the design and planning model as proactive inputs to face the potential cost impacts as well as to achieve desirable benefits. A feature of the model is to incorporate performance of the SC relative to benchmark /target values and consider options to reduce gaps for improving overall sustainability performance of the business. The model considers measurable key characteristics of the factors in a closed loop SC to have a tangible effect on the bottom line and improve the company's image to customers with a keen view of sustainability in mind. The research outcomes show effectiveness of the proposed target based planning to pinpoint crucial sustainability indices and select appropriate options to improve the indices and overall performances within desirable bounds on cost. A numerical example is illustrated to aid managers to design and plan such SCs for their businesses.

Keywords: *sustainability factors and practices; environmental and economic sustainability; social responsibility; multi-objective mathematical model.*

1. INTRODUCTION

Several progressive organizations have been adopting sustainability as an integral part of their business strategy to become socially responsible and to improve overall company image and performance. Customer pressure, government regulations, and market image are drivers of such adoptions. In fact, organizations must strive for such adoptions as a part of strategic imperatives to align customer focus, efficiency, quality, and responsiveness (Greene, 2012). Sustainability is becoming a crucial consideration for society in policy dialogues for various international organizations (Ahi and Searcy, 2015) due to the visible impact of climate change, resource scarcity (energy, materials), and biodiversity loss. The inclusion of sustainable practices in SC operations not only addresses social responsibility and caters to customer preferences, but also improves operational performance to reduce cost, enhance product quality, and enable compliance with regulatory requirements (Wu, et al., 2014). There are example companies such as GE, Unilever, and Nike that have been achieving impressive overall performances by following innovative sustainability models. Since sustainability helps to attain an optimistic future (Govindan, 2016), organizations have been pursuing this changed strategy of adopting sustainability and are moving out from a narrow focus on profit and profitability to a broader "triple bottom line" focus on profit, people and planet (Besiou and Wassenhove, 2015). Based on interviews with global business thought leaders and executives, sustainability has been mentioned as an integral part of value creation (Berns, et al., 2009).

An operational definition of sustainability includes environmental management, closed loop supply chains, and a broad perspective on triple bottom line thinking, integrating profit, people, and the planet into the culture and strategy of the company operations (Kleindorfer et al., 2005). As such, study and analysis of various operational practices and factors to improve sustainability is a vital requirement for SCs to obtain improved performance (Tajbaksh and Hassini, 2015). There have been several studies on evaluation of sustainability performances of SC operations (Eskandarpour, et al., 2015). Such performance metrics are often required as competitive priorities for the stakeholders to justify investments (Govindan, 2016). Since environmental and economic sustainability metrics and overall SC objectives are often conflicting, Lee and Billington (1992) consider establishment of a performance measurement system to facilitate effective management of SC to make informed decisions. In addition, performance metrics create a basis to measure and identify gaps with the target or benchmark companies that are considered to have superior sustainability performances. The gap based analysis facilitates an organization to plan steps to achieve targeted performance by considering factors and their interactions responsible for such performances. Due to the complex nature of interactions in a dynamic business environment, a performance-based approach does not provide an accurate picture in some cases (Tajbaksh and Hassini, 2015). But, when an organization is planning to improve sustainability performances related to a factor, having a target may be considered to be more important than optimality.

Based on the literature, standards, established practices of superior-performing companies, and compliance requirements by regulatory authorities, factors responsible for environmental sustainability may be identified (OECD, 2000; ISO 26000; GRI sustainability reporting guidelines, ISO 14000 (ISO 2002)). Social sustainability/responsibility is an emerging phenomenon. This study addresses social sustainability performance in select cases directly, such as: safety, training, suggestion box, grievance procedures, and employee turnover. Environmental performance improvement initiatives may be considered as a part of social responsibility (Tate et al., 2012). This research addresses it as well.

Environmental sustainability performance metrics may be defined to estimate the impact/influence of the identified sustainability factors of relevant SC functions on the environment (European Union (EU), EPA, ISO 14001 (ISO 2002)). Measures for economic sustainability and social responsibility may similarly be defined following the literature. In addition, performances of environmental sustainability factors often times influence economic performance of SC (EPA 2000; EPA 2016) and select social responsibility. Considering all these issues, a SC should decide on a target and/or benchmarked performance. While the literature includes several studies for performance measurement and improvement of sustainability performance, to the best of our knowledge, this is the *first study* that introduces a *comprehensive SC plan* to identify sustainability performance gaps and to include an appropriate model-based approach to close the gap to achieve a targeted performance by a SC.

The remainder of this paper is presented in five additional sections. The next section presents a brief literature review on SC sustainability. This is followed by the problem statement and definitions of metrics. Thereafter, a mathematical model for integrating sustainability in the design and planning of supply chains is presented. A numerical example illustrates applicability of the model. Finally, the research is summarized through a discussion and conclusions section.

2. LITERATURE REVIEW

Three streams of research that are relevant to this paper are environmental sustainability management, closed loop supply chain, and supply chain sustainability and triple bottom line. Each of these streams study literature pertaining to various SC factors that influence strategic decision making in the design and planning of SC to achieve economic and environmental goals, and to some extent social sustainability as well.

2.1 Environmental Sustainability Management

Integration of environmental management in product design and development, shop floor control, and in logistics and SC, has been recommended in the literature as best practice to address concerns on climate change and effect on community health and safety from industrial activities (Corbett and Kleindorfer, 2001). Since many companies outsource a share of their production process and procure components, subassemblies and similar items from suppliers, overall environmental performance of an organization is influenced by the environmental performance of their suppliers (Tate et al., 2012). Within supply management, SME type suppliers often need support from the buying firm to address environmental requirements (Lee and Klassen, 2008) set by the buyer. Supporting suppliers by providing training and other resources is found to be effective for improving environmental performance (Porteous et al., 2015). Based on different metrics for the three areas of economic, environmental and social responsibility, Sarkis and Dhavale (2015) proposed a Bayesian framework and a Monte-Carlo simulation to rank suppliers in the evaluation process.

Business leaders and academicians have been emphasizing the importance of improving environmental sustainability (Vision 2050, WBSCD). In addition, it is now quite established that a firm's business performance is linked to its environmental practices (Hollos et al., 2012).

Adoption of an environmental management system, such as ISO 14001, is considered as a factor that includes a wider effort to reduce SC environmental impact (Wiengarten et al., 2013). Other than ISO 14001, carbon footprint and consumed energy level following ENERGY STAR are considered as metrics to gauge environmental performance (Gaussin et al., 2013). Additional environmental metrics include: use of water, materials, and reduction of hazardous substance and harmful emission generation in addition to management of water and materials waste by recovery and reuse (Porteous et al., 2015).

Prior literature also covers a model-based approach (Raz et al., 2013) to integrate economic and environmental implications of a firm's design decision to maximize profit. A review study by Eskandarpour (2015) included 74 research papers (1991 to 2014) that considers environmental SC network design models.

2.2 Closed Loop Supply Chain and Economic Sustainability

Closed loop SC planning for maximizing profit or minimizing cost may be considered as economic sustainability based research. In this subsection, closed loop SC as well as research that address environmental and economic sustainability together, are reviewed. Based on the fact that resource conservation and reduction of waste are the two crucial issues for sustainability to meet resource scarcity of the world (Bing et al., 2015), a reverse SC network for recycling that minimizes cost and environmental impact may be considered quite important. But, as is evident, recycling or reprocessing of waste generates pollutants. So a tradeoff scheme or mechanism (energy trading scheme, ETS) is needed between economic efficiency from recycling of waste and its impact on the environment. Bing et al., (2015) proposed an integer programming based closed loop SC model and the results showed a reduction in total cost and total transportation emission. Emission trading scheme studied in Chaabane et al., (2012) is a similar trade-off approach between economic and environmental objectives for emissions to improve overall SC sustainability.

Closed loop SC and thereby product recovery are considered *green SC* activities that integrate value added activities and minimize environmental impact (Abdullah et al., 2012). Abdullah et al. conducted a study by considering the effect of inventory, location of retailers, distribution, and recovery centers in a reverse SC. They proposed supporting of eco-friendly activities (such as reverse supply chain, re-manufacturing) by the government by paying incentives for green activities. Under these incentive-based systems, organizations pursuing green activities receive carbon credits, which they are able to sell to earn profits. Military SC may be considered almost a similar situation (Wilhite et al., 2014). In a military SC, demand for a military weapon system is very low, so a SC needs to create incentives for the supplier.

Imposition of carbon tax is used by governments as a regulatory tool to control carbon foot prints and thereby improve environmental concerns from harmful emissions.

Fahimnia et al. (2013) considered environmental performances of the SC in terms of a carbon tax imposed by the Australian government in their study.

2.3 Sustainable Supply Chain and Triple Bottom Line

Sustainability performance can be linked to SC planning and decision making process to achieve a targeted performance. Ahi and Searcy (2015) proposed a mathematical modeling based approach to evaluate sustainability performance of the SC based on enablers and barriers to SC sustainability.

Boukherroub et al., (2015) proposed a multi-objective mathematical model that considers performance criteria in the SC functions for: a) economy: in terms of financial performance, responsiveness, flexibility, and quality; b) environment: in terms of resource consumption, climate change, hazardous materials and pollution; c) society: in terms of health and safety, job creation and wealth, and work conditions. They applied a model based on their defined measures in a Quebec based Canadian lumber industry case.

A review study by Eskandarpour et al. (2015) reported ten research papers (1991-2014) that considered all three dimensions of sustainability. Common social sustainability factors/ practices considered in these papers are: social justice, supplier human rights actions, labor conditions, supplier compliance with child labor laws, and delivery of social equity. To have a better SC performance, each of the dimensions needs to be integrated in SC management and planning (Seuring and Muller, 2008a). Interactions and inter-dependence between the dimensions are to be considered by following a win-win approach for improved sustainability performance.

To address sustainability of products, increased communication, delineation of buyer- supplier links, and supplier development have been given importance in the literature (Seuring and Muller, 2008b). Ahi and Searcy (2015) proposed a mathematical modeling based approach to evaluate sustainability performance of the SC based on enablers and barriers to SC sustainability.

This research considers sustainability factors similar to those in the literature, but with *some additions* for each of the SC functions. It formulates sustainability metrics and plans improvement steps to close the gaps between existing and targeted performances.

Table 1 Highlights of contribution of this research compared to the select recent and highly cited literature

Sustainability Factors in SC Functions	Comparison with select Literature
Production	Factors addressed
p1) Lower Scrap rate; **p2**) modular design; **p3**) energy efficient plant; **p4**) lower CO_2 generation; **p5**) Machine Reliability and Plant capability; **p6**) Ensured quality product; **p7**) Advanced technology plant to lower energy use; **p8**) OSHA compliance; **p9**) Number Employee training;**p10**) Employee turnover; **p11**) improvement Suggestions by employee; **p12**) environmental regulatory compliance for hazardous waste, pollutants, water and others; **p13**: community skill training for employment improvement as a part of social responsibility. **p1, p3, p4, p6,** and **p7**: contribute to environmental; Each one of these and **p2, p5, and P8** contribute to Economic **; p8, p9, p10, p11, p12, and p13** contribute to Social sustainability**.**	Acquaye et al. (2018): p4 and p7 mainly. Sodhi and Tang (2017): p8, p9, p10, p11and indirectly relates to others. Sarkis and Zhu (2017): p1 to p12 through greening process. Bendul et al. (2017): p2, p8, and p9. Rajeev et al. (2017): p2, p4, p8, p11 and p12. Zhang, et al. (2018): p1, p2, p3, p4, p5, p6, p7, p8, and p13. Mathivathanan et al. (2018): p1 to p6, p10, and p11. Laurin and Fantazy(2017): p1 to p4, p8 to p12. Eskandarpour et al. (2015): social justice, supplier human rights actions, and labor conditions. Corbett and Kleindorfer(2001): p2,p3,p4, and p12. Kleindorfer et al. (2005): p1 to p13. Boukherroub et al., (2015): p1, p3, p4, p5, p6, p8, p12, and p13. Chaabanee et al. (2012): p1 to p12.
Transportation and Distribution	
Transportation and Distribution **td1**) Lower fuel consumption; **td2**) Lower CO_2 generation; **td3**) environment friendly transportation mode; **td4**) optimum assignment of route	Bendul et al. (2017): td1, td2, td3, and td4 Acquaye et al. (2018):td1, td2, td3, and td4. Sodhi and Tang (2017): td1 to td4. Sarkis and Zu (2017): td1 to td4.

	Rajeev et al. (2017): td1 td2, td3 and td4. Mathivathanan et al. (2018): td1 to td4. Laurin and Fantazy(2017) : td1, td2 and td3. Corbett and Kleindorfer (2001): environmental practices in outgoing logistics. Kleindorder et al. (2005): td1 to td4. Boukherroub et al. (2015): td1 and td2. Bing et al. (2015): td1, td2 and td4. Chaabanee et al.(2012): td1 to td4
Supply Management	
sm1) Partnering relation for flexibility in accommodating order and design changes; **sm2**) No Receiving inspection; **sm3**) responsive to support low inventory; **sm4**) supplies with low energy consumption; **sm5**) maintains quality system-lower scrap, rejection; **sm6**) lower generation of harmful emission; **sm7**) reliable machine.**sm8**) employee safety; **sm9**) employee turnover and employee training; **sm10**) supporting supplier by training and development.	Acquaye et al. (2018): sm2, sm4, sm5 and sm6. Tang and Sodhi (2017): sm1 to sm10. Sarkis and Zhu (2017): sm1 to sm10. Bendul et al. (2017): sm1 and sm10. Rajeev et al. (2017): sm1 to sm10 Zhang, et al. (2018) sm1 to sm10. Mathivathanan et al. (2018) sm1 to sm10. Laurin and Fantazy (2017): indirectly sm1,sm4, and sm5 to sm10. Eskandarpour et al. (2015): supplier compliance with child labor laws and social equity. Corbett and Kleindorfer (2001): directions to address environmental concern. Boukherroub et al. (2015): social factors employee health and working condition. Kleindorfer et al. (2005) broadly covered sm1 to sm10. Chaabanee et al. (2012) broadly covered sm1 to sm10
Recovery and Remanufacturing	Comparison with select Literature
rm1) partnering relation with recovery service providers; **rm2**): recovery quality -low rejection/scrap rate; **rm**3) disposal of wastes according to regulation; **rm4**) safety of the employees; **rm5**) employee turnover and employee training; **rm**6) quality assurance for recovery; **rm7**) reliability of the equipment; **rm8**) low energy consumption for the recovery; **rm9**) lower generation of harmful emission.	Acquaye et al. (2018): rm3, rm8, and rm9. Sarkis and Zhu (2017): rm1 and rm9. Bendul et al. (2017): rm1, reduced packing equivalent to rm2 and rm7. Rajeev et al. (2017): rm1 to rm 9. Zhang et al. (2018): rm1 to rm9. Mathivathanan et al. (2018): rm1 to rm 9. Laurin and Fantazy(2017):reverse logistics on take back packaging cardboard for recycling.. Corbett and Kleindorfer (2001): directions for the reverse logistics. Bing et al. (2015): rm1 to rm5, rm8, and rm9. Kleindorfer et al. (2005): rm1 to rm4; rm8 and rm9 Chaabanee et al. (2012): rm1 to rm9 broadly.
Methodological comparison	
Mathematical Modeling of Sustainability metrics	Acquaye et al. (2018): Total Carbon emission as the metrics for SCs. Zhang, et al. (2018): metrics for sustainable management practices. Mathivathanan et al. (2018): s model uses decision making trial and evaluation for automotive sustainable SC management practices. Ahi and Searcy (2015): evaluated sustainability performance of the SC for

	enablers and barriers for triple bottom-line based factors. Boukherroub et al. (2015): model based approach for the environmental, economic and social sustainability factors to determine SC's overall performance based on a Canadian Lumber Industry case. Bing et al., (2015): closed loop SC model for recycling that minimizes cost and environmental impact.
Empirical Evaluation	Bendul et al. (2017): studied sustainability factors for 18 products based on case studies that are marketed and manufactured mainly in China, India and Ghana by Multinational local companies following a SCOR framework. Zhang, et al. (2018): validated their sustainability metrics through empirical analysis based on collected data from 293 Chinese manufacturers. Mathivathanan et al. (2018): interrelationships between various stake holders and sustainability factors of the automobile business. Laurin and Fantazy(2017): a single Case study based approach that explores IKEA Sustainability practices.
Literature Review on Sustainable SC Discussion based analysis on literature findings	Sodhi and Tang (2017): Social sustainability following a thematic approach as described under **Production** factors. Sarkis and Zhu (2017): Thematic topics: product, process, technology, strategy and energy related to environmental sustainability mainly. Rajeev et al. (2017): Sustainable SC research from 2000 to 2015 based on triple bottom lines pillars. Eskandarpour et al. (2015): review of 10 research papers for social responsibility only. Corbett and Kleindorfer (2001): State of the art critical analysis and framework for environmental priorities in the extended SC. Kleindorfer et al. (2005): Review study of sustainability covered in the first 50 issues of POMs.
Note: on the uniqueness of this Research	
This research considers sustainability metrics for Production factors p1 to p13; Supply Management factors sm1 to sm10; Transportation and distribution factors: td1 to td4; and Recovery Service management metrics rm1 to rm9 and integrated the performance metrics in the sustainable SC design and planning model. Most of the research reviewed considered the factors in descriptions only, not as metrics for performance evolution. Limited research that considered the metrics based factors do not include the option to include the metrics in the sustainable SC design. Very few research considered environmental, economic and social sustainability in the SC planning and operations. Within the metrics considered in this research, sustainability factors for employee training, reliability of equipment, employee turnover, and scrap rate are unique. Supporting the supplier by training and development are unique to this research in addition to uniqueness for integrating sustainability metrics and target based approach in SC design	

3. RESEARCH METHODOLOGY

This research follows a mathematical modeling based approach for the design and planning of sustainable SCs.

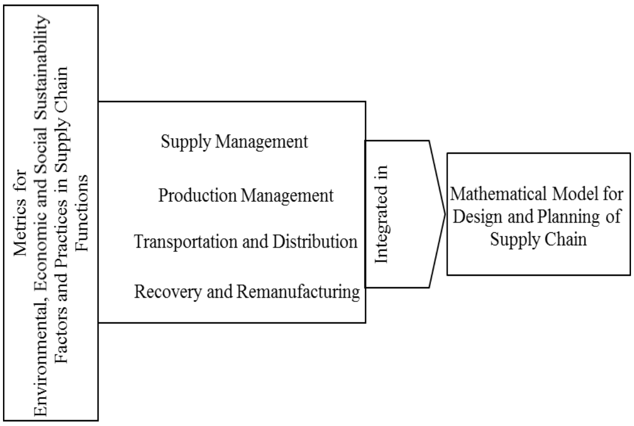

Figure 1 Schematic representation of the research methodology

The research first defines sustainability metrics for supply chain functions which are then integrated in the design and planning model of the SC to achieve desired sustainability performances based target set by the SC management. **Figure 1** presents the schematic view of the research methodology.

3.1 Problem Statement and Definitions of Metrics

The study is unique in formulating new and practicable sustainability metrics for the considered factors that can be integrated in the decision models to facilitate *target based planning* by the SC managers to achieve a desired level of sustainability performance.

The objective of the research is to *integrate sustainability criteria* in the *design and planning* of a SC process to improve market image and overall sustainability (economic, environmental and social) performance of the company. There is limited research on sustainable SC *management* metrics. The metrics covered in the extant literature are suitable for monitoring sustainability performances but are *not suitable* for integration in a *SC planning model* for improvement of sustainability performance (e.g. Searcy et al., 2007, Vachon and Mao, 2008). A literature review in Hassini et al., (2012) covered similar research on metrics. A review of modeling based sustainable SC management research (Seuring, 2013) and a study in Eskandarpour et al., (2015) suggested developing a modeling based approach for *general applicability*. In addition, Eskandarpour et al. (2015) mentioned that modeling based research should go beyond the narrow scope of current models to include *social sustainability metrics*. Our research addresses these issues that are not dealt with in prior papers.

The model proposed in our research is unique. It formulates sustainability metrics to evaluate SC functions for environmental, economic and social sustainability and determines the *gap* with the *desired level of the metric value* such that SC management can decide to close the gap and improve their sustainability performance. Although our model is formulated for welding machines, the approach is quite generic in nature for defining the metrics, setting targets, and analyzing gaps. It then *integrates gaps* in the *SC planning* process and provides options to *SC management* for improving overall business performance.

Suppose an SC produces different types of products *P* ($p \in P$), similar to arc welding transformers, MIG (metal inert gas), and TIG (tungsten inert gas) welders manufactured and marketed by Miller, ESAB, or Lincoln. Products *P* are marketed as two types T($t \in T$), new and remanufactured. The products follow a modular design. Let $i \in I$ denote the SC functions (supply, production, recovery and training management). The new products are made by a set of new modules $m \in M$ supplied by a set of quality affiliated suppliers out of pool of enlisted suppliers I^s ($s \in I^s$), affiliated by considering quality based criteria following (Das, 2011). Based on this criterion, equation (1) is defined to identify quality affiliated suppliers. Here based on the market expectation the SC sets an overall qualifying score *TQS* for sustainability metric QS $q \in E^q$ for a supplier to become affiliated to supply module. Let SP_{sq} is the score by a supplier for metric *q*. Parameter AS_s identifies quality affiliated supplier *s*, AS_s=1 when the supplier is affiliated; 0 otherwise. Quality affiliated suppliers are assigned supply orders to manufacture the modules by assembling a set of new components ($c \in C$). Detailed definitions on supplier affiliation metric QS are presented in the Appendix.

$$AS_s TQS \le \prod_{q \in Q} SP_{sq} \qquad \forall s \in S \tag{1}$$

The SC manages production of new and re-manufactured product by assembling modules and performing other necessary steps in a set of plants. Production order is assigned to a set of quality capable plants out of Production plants I^j ($j \in I^j$). Quality capable plants are identified by considering set of plant sustainability metric following quality capability determination criteria presented in Das (2011). Based on this criterion equation (2) defined below identifies the quality capable plants. The parameter PC_j identifies quality capable plant *j* ; PC_j=1 when plant *j* is quality capable; 0 otherwise. Let *ES* be the overall qualifying score set by the SC for assigning production to a plant based on plant sustainability metric PS $n \in E^n$. Let PP_{nj} be the score by a plant *j* for sustainability metric *n*. Detailed definitions for plant sustainability metric PS are presented in the Appendix.

$$PC_j ES \le \prod_{n \in E^n} PP_{nj} \qquad \forall j \tag{2}$$

The remanufactured products are made by the recovered and quality enhanced module *m* obtained from customer returns through a set of quality affiliated recovery service providers (RSP) out of a pool of enlisted RSPs, I^v($v \in I^v$) following similar criteria presented above for supplier affiliation and plant capability determination. Equation (3) defined below identifies quality affiliated RSPs. Let *VC* be the overall qualifying score set by the SC to identify qualified RSPs and $RR_{vq'}$ denotes the score for recovery sustainability metric RS $q' \in E^{q'}$ by a RSP *v*. Parameter RS_v identifies quality affiliated *RSP v* ; RS_v =1 when RSP *v* is quality affiliated ; 0 otherwise.

$$RS_v VC \le \prod_{q' \in E^{q'}} RR_{vq'} \quad \forall v \tag{3}$$

Detailed definitions for recovery sustainability metric RS are presented in the Appendix.

The SC plans to improve a set of sustainability performance metrics E ($e \in E$) for each function i. Let Es, E^j, E^v and E^τ be the partitions of E to represent the sets of sustainability metrics applicable to supply, production, recovery, and training management, respectively. Suppliers and RSPs are in collaborative relationship with the SC and participate in different quality, productivity, environmental, and other sustainability related training sessions organized by the SC. The suppliers, I^s and RSPs I^v, differ in price, quality, and sustainability performances for supplying different new and recovered modules, respectively.

Please see the **Notations** used for Model formulation in the APPENDIX.

3.2 Re-manufactured and New Product Volume for Economic Sustainability

Based on an analysis presented in the APPENDIX document, the SC decided to cover 50% of its overall product demand with remanufactured product and the remainder with new product. Based on market survey on secondhand and remanufactured products for similar products, the SC is planning to set selling price at 50% of the new product price to have approximately a 10% market growth per year of remanufactured product. A justification for this assumption is validated by Pang et al. (2015) who considered an electronic product in their study. They reported a 10% price differential between new and remanufactured product that generally may lead to a growth rate of 10% per year for remanufactured product. Further, Tang and Tomlin (2008) used a uniform distribution for market demand change. While these selected values are used in an illustrative example, analysis and the inferences can be easily extended to other values.

The SC also planned to achieve remanufacturing unit cost to be 45% of new product unit manufacturing cost to maintain an overall profit for the company at least equal to that in the previous year (see the analysis in the APPENDIX). To restrict the chance of cannibalizing new product volume by the remanufactured ones with lower price and equivalent quality, the SC controls collection of customer returns. Such control on collection of customer returns also supports avoiding cost of carrying recovered module inventory and facilitates economic sustainability.

3.3 Mathematical Model

The research includes two major objectives: 1) maximize overall sustainability by minimizing overall gaps in sustainability metrics with benchmarked metrics; and 2) maximize profit. It is apparent that these objectives are conflicting to each other.

Sustainability Performance Improvement Objective

Based on the study of sustainability criteria in the literature and performance metrics for several companies with impressive sustainability performances over the last several years, suppose the SC, considered in the problem statement, decided on benchmarked performance for each metric applicable to their own SC functions. Based on such information, the **Objective 1** in equation (4) minimizes *SUS*, the overall SC sustainability performance gap for SC functions as defined in equation (4.a), where gp_i denotes the gap for SC function i (supply, production; recovery management; and community engagement).

Objective 1: minimize *SUS* (4)

$$SUS = \sum_{i \in I} gp_i \tag{4.a}$$

Equation (5) defines sustainability performance gap(gp_i) for each function i by considering benchmarked performance BS_{ie} for sustainability performance metric e pertaining to function i, GS_{ie}, the current sustainability performance and the options (the last term of the equation) for improving sustainability performance of the function. Constraint (6) ensures selection of one option for performance improvement.

$$gp_i = \sum_{e \in E} \left(BS_{ie} - GS_{ie} - \sum_{o \in O} PI_{ieo} w_{ieo}\right) \quad \forall i \in I \tag{5}$$

$$\sum_{o \in O} w_{ieo} \le 1 \qquad \forall i, e \in E \tag{6}$$

The SC management plans to undertake investments for the options involving technology (Vachon , 2007), selection of new materials, change of design including waste treatment plant and procedures, automation, and providing training and similar other measures based on the potential to achieve benchmarked performance.

Estimation of Potential Benefit by Minimizing Sustainability Performance GAP

Through a study of its industrial customers, retailers, and select user segments, usually the customer segment that provides high importance to green and sustainable practices will agree to pay premium prices for the product manufactured by a company that pursues sustainable approaches; several organizations, such as GM reduced $12 million of their costs by using reusable containers (one of their sustainability steps); Commonwealth Edison saved $12 million through effective resource utilization showing evidence of achieving cost reduction and demand growth with good sustainability performances (see EPA, 2000). Cost reduction results in market/demand growth because organizations utilize such savings to get a price advantage (Kleindorfer et.al., 2005) in addition to improvement in quality and productivity. Kleindorfer et.al., also mentioned that people's awareness on triple bottom line also contributes to increased product demand. A sustainable company creates such awareness through their business processes, product image, and advertising their contributions to society through improvement of environmental and social sustainability. This study assumes that by achieving sustainability performance for their supply, production, and recovery management close to the benchmarked level, the SC can achieve a desired market growth that is based on a uniform distribution U(l, h). Such an assumption may be considered logical based on the cost reduction examples presented above from EPA (2000) in addition to findings in Berns et al., (2009) related to "How Sustainability Affects Value

Creation" based on examples of successful companies. Note that this example is for an illustration. Other distributional assumptions may be easily incorporated in the model based on specific situations.

Let the market growth effect for SC function i be represented as $GR(i)$, if the SC achieves the benchmarked performance level by reducing gaps gp_i for the function. Suppose the growth for each of the functional areas is equally likely such that total growth follows a uniform distribution, U (l, h). To model the impact of achieving sustainability performance it is logical to assume that the growth is highest when performance gap from benchmarked level is 0, and the growth is 0 when gap is at the current level (no reduction). Similar influence of sustainability performance gap reduction is assumed in the case of cost reduction also (EPA, 2016).

Let d_{pt} denote the average demand for product p of type t (new and re-manufactured) and the assumed total demand growth rate be $GR(d)$; where $GR(d)=\sum_{i\in I}(1-gp_i)GR(i)$. Since growth is related to minimizing the gap with benchmarked performances for the functions under considerations, the demand will become $d_{pt}(1+\sum_{i\in I}(1-gp(i)GR(i))$. Let the effective demand after considering overall growth be represented by equation (7)

$$ed_{pt}=d_{pt}(1+\sum_{i\in I}(1-gp_i)GR(i)) \qquad \forall p,t \tag{7}$$

Let the cost reduction target that SC strives to achieve be described as $RE(i)$ which varies randomly according to a uniform distribution U(cl, ch). Again, this consideration is based on prior research (Tang and Tomlin, 2008). In addition, this is used to discuss the implications of the inferences drawn from the model solutions. Extensions to the model based on other chosen distributions and products are straightforward. Let the current average cost of a product p, of type t, be CP_{pt}. Since growth is uncertain, this average cost is also uncertain until realized growth is determined. However, the planning model should consider a target cost in order to improve economic sustainability. We have

$$EC_{pt}=CP_{pt}(1-(1-gp_j)RE(j)) \qquad \forall p,t,j\in I^j \tag{8}$$

Let the effective supply cost for new modules, after considering improvement of sustainability, be given by:

$$ECZ_{ms}=CZ_{ms}(1-(1-gp_s)RE(s)) \qquad \forall m,s\in I^s \tag{9}$$

Similarly, let the reduction in recovery cost be assumed to follow a uniform distribution U(vl,vh). This assumption is for illustration of the results based on previous discussion. Let the effective cost of a module, after considering reduction, be ECR_{mv}, given by:

$$ECR_{mv}=CR_{mv}(1-(1-gp_v)RE(v)) \qquad \forall m,v\in I^v \tag{10}$$

It may be mentioned here that there will be a cost increase for investing in options to reduce the sustainability gap gp_i. Such fixed costs and other implementation costs will be accounted for in the production, supply, recovery and distribution cost functions.

<u>Profit Maximization Objective and Overall Planning</u>

Objective 2 in equation (11) maximizes profit that is defined by equation (12) by adjusting revenue (RV) earned with total cost (TC) of SC operation. Revenue (RV) is computed in equation (13) considering market price, demand, and demand growth according to equation (7) for the products. Here we assume that total production is equal to effective demand. Equation (14) describes total cost in terms of its components.

Objective 2: maximize *Profit* (11)

$Profit = RV - TC$ (12)

$$RV=\sum_{p\in P}\sum_{t\in T}VP_{pt}\left[\sum_{j\in I^j}x_{pjt}\right] \tag{13}$$

where TC = Production cost (PC) +New module supply cost (SPC) +Recovered module cost (RMC) + penalty cost for electrical fuel energy (EGC*Penalty factor) + penalty cost for harmful emissions (EMC*Penalty factor) +social sustainability program cost (SSC) (14)

The first component of TC, the production cost (PC) is computed in equation (15). PC includes cost of production after considering the effect of cost decrease according to equation (8); fixed cost for assigning production to a plant, and fixed investment cost for sustainability improvement options.

$$PC=\sum_{p\in P}\sum_{t\in T}EC_{pt}\left[\sum_{j\in I^j}x_{pjt}\right]+\sum_{p\in P}\sum_{j\in I^j}PC_jFPC_j+\sum_{i\in I^j}\sum_{e\in E^n}\sum_{o\in O}FPI_{ieo}w_{ieo} \tag{15}$$

$$SPC=\sum_{s\in I^s}\sum_{m\in M}zs_{ms}ECZ_{ms}+\sum_{s\in I^s}AS_s\sum_{m\in M}FSC_{ms}+\sum_{I\in I^s}\sum_{e\in E^q}\sum_{o\in O}FSI_{ieo}w_{ieo} \tag{16}$$

$$RMC=\sum_{p\in P}CC_Prx/(1-waste)D_p+\sum_{m\in M}\sum_{v\in I^v}rz_{mv}ECR_{mv}+\sum_{v\in I^v}RS_v\sum_{m\in M}FRC_{mv}+\sum_{i\in I^v}\sum_{e\in E^{q'}}\sum_{o\in O}FRI_{ieo}w_{ieo} \tag{17}$$

$$EGC=\sum_{p\in P}EEP_p\sum_{t\in T}\left[\sum_{j\in I^j}x_{pjt}\right]+\sum_{m\in M}\sum_{s\in I^s}zs_{ms}EES_{ms}+\sum_{m\in M}\sum_{v\in I^v}rz_{mv}EER_{mv}+ \\ \sum_{p\in P}\sum_{t\in T}\sum_{j\in I^j}DD_jx_{pjt}\,FE/STL_p \tag{18}$$

$$EMC = \sum_{p\in P} EMP_p \sum_{t\in T} \sum_{j\in I^j} x_{pjt} + \sum_{m\in M}\sum_{s\in I^s} zs_{ms}EMS_{ms} + \sum_{m\in M}\sum_{v\in I^v} rz_{mv}EMR_{mv} + \sum_{p\in P}\sum_{t\in T}\sum_{j\in I^j} DD_j d_{pt} FE / STL_p \quad (19)$$

$$SSC = \sum_{g\in I^g} TI_g \sum_{\tau\in E^\tau} nED_{g\tau} + \sum_{i\in I^g}\sum_{e\in E^\tau}\sum_{o\in O} FTI_{ieo} w_{ieo} \quad (20)$$

$$PC_j \in \{0,1\}, \forall j \in I^j; RS_v \in \{0,1\}, \forall v \in I^v; AS_s\{0,1\}, \forall s \in I^s; w_{ieo}\{0,1\}, \forall i,e,o \quad (28)$$

The next component of *TC*, the new module supply cost (*SPC*) is defined in Equation (16). *SPC* computes supply cost of new modules to fulfill demand growth by considering cost reduction of modules according to equation (9), fixed cost for ordering, and fixed costs for implementing sustainability improvement options.

Equation (17) computes recovered module cost (*RMC*) by considering collection cost of returns, recovery cost after including the effect of minimizing sustainability metric gap of the RSPs according to equation (10); fixed cost for ordering, and fixed costs for implementing sustainability improvement options.

Equation (18) computes estimated amount of energy spent for production of product; realization of new modules by suppliers; recovery of modules by RSPs; and fuel energy needed for transportation and distribution of products; average distance traveled by a trip between production plants and retailers and number of trips needed based on total transferred amount. Fuel energy spent in transportation was estimated considering standard per mile fuel energy consumption by standard size semi-trailer (truck) load according to US Department of Transportation data and total distance travelled for the trips. The transformation of *EGC* in MJ is done by multiplying with a penalty/transformation factor of 0.056, based on 3.6MJ = 1kWh, price of 1 kWh = $0.20 for industrial consumer, (1/3.6)*0.20 = 0.056. In TC computation, *EGC* is multiplied by 0.056:

Equation (19) computes estimated generation of harmful emissions for production of product, realization of new modules by suppliers, recovery of modules by RSPs, and generation of emission for transportation and distribution of products in equivalent kg of CO_2.

Penalty cost due to total harmful emissions, *EMC*, in equivalent kg of CO_2 is computed by considering a penalty as imposed by the Australian Government based on per ton of equivalent CO_2 generation. Here, a penalty factor of 0.051 is used (based on *EMC* in kg/(1000 kg/ton) *$51 /ton penalty). In TC computation, *EMC* is multiplied by 0.051:

Equation (20) computes social sustainability program related cost by considering the costs for conducting the training and fixed cost for installing improvement option to increase enrollment.

Equation (21) defines demand for new and re-manufactured product based on SC decision. Such decisions may be taken based on analysis in equations (29) and (30) (given under APPENDIX). Equation (22) computes new modules requirements to fulfill market demand and equation (23) ensures assignment of new modules to qualified suppliers. Similarly, equation (24) computes the number of recovered modules to fulfill requirements of re-manufactured product and equation (25) ensures assignment of recovery of modules to qualified RSPs. Constraint in equation (26) balances production with effective demand defined in equation (7). Constraint in equation (27) assign production only to the qualified plants. Constraint (28) imposes integrality:

$$nxD_p = \sum_{t\in 1} d_{pt} \text{ and } rxD_p = \sum_{t\in 2} d_{pt} \quad \forall p \quad (21)$$

$$\sum_{p\in P} \rho_{pm} \sum_{t=1} \sum_{j\in I^j} x_{pjt} = \sum_{s\in I^s} z_{ms} \quad \forall m \quad (22)$$

$$z_{ms} \le AS_s BN \quad \forall m, s \in I^s \quad (23)$$

$$\sum_{p\in P} \rho_{pm} \sum_{t=2} \sum_{j\in I^j} x_{pjt} = \sum_{v\in I^v} rz_{mv} \quad \forall m \quad (24)$$

$$rz_{mv} \le RS_v BN1 \quad \forall m, v \in I^v \quad (25)$$

$$ed_{pt} = \sum_{j\in I^j} x_{pjt} \quad \forall p,t \quad (26)$$

$$x_{pjt} \le PC_j BN3 \quad \forall p, j \in I^j, t \quad (27)$$

4. NUMERICAL EXAMPLE

This section illustrates applicability of the model considering an example SC. Discussion in this section emphasizes the solution procedure and model results. The model is solved for this example problem in a Dell Latitude Series PC with Intel® core TM i7-4810MQ CPUb @2.80 GHz, 2.80GHz with 8.00GB memory, using commercial solver LINGO 14 that took at an average 5 minutes for each solution step. This section presents limited input data when such data are needed to analyze the model outcomes. We assume that the SC markets 5 products with manufacturing being done in their 6 plants. As discussed before, the products are similar to arc welding transformers, MIG and TIG as manufactured by Miller, ESAB or Lincoln.

Table 2 presents the average product demand (D_p) in their respective market considering that the entire market is for new product. The values were generated randomly to illustrate results. Obviously, based on product choice, other distributions could easily be utilized.

Table 2 also shows SCs decision to market 50% of this average demand as new product (d_{pt} for t=1). Considering a 10% market growth, (50%+10%)=60% of this average demand is planned for marketing as re-manufactured product(d_{pt}, t=2). Such a decision is taken based on the analysis given in the APPENDIX document. As discussed before, the SC controls collection of customer returns to control cannibalization of new product by remanufactured one. Through controlling collection, the SC also ensures returns to have modules required for (50%+10%) of their demand considering 10% demand growth for remanufactured product. Considering 20% modules from customer returns are non-usable or scrap based on past data, the SC plans to collect (60/(1-0.2))%= 75% of their demand to obtain usable modules for 60% of their demand. The assumption of 20% average scrap out of returned products is reasonable because it varies for different products and markets and may also vary year to year based on company policy and expertise of inspector engaged in sorting the returnable. Such an assumption is made based on past data of returnable.

As discussed before, the SC follows a modular product design. According to this design, 6 to 7 modules out of 18 modules form each product. Each module is formed by 4 to 8 components out of 25 components. **Table 3** shows a typical product formation by modules and module formation by components.

Table 3 Typical product and module formation data.

	Product 1	**Product 2**	**Product 3**
Modules	2,7,11,13,15,18	1,3,6,9,10,12,16	1,2,7,10,13,17
	Module 1	**Module 2**	**Module 3**
Components	1,2,3,24,25	4,5,6,7,22,23, 24	12,13,14,15

New modules are supplied by a pool of 9 suppliers. The SC has partnering relations with suppliers, and as a part of overall sustainability requirements they have provided several training programs in lean, quality assurance, cost improvement, environmental, and social sustainability to their suppliers.

The SC follows a closed loop SC system and respects social responsibility to address environmental and economic sustainability requirements as much as possible. The SC collects customer returns through their retailers by paying incentives to the customer as part of a contract with the retailer following the Re-manufacturing Sustainability Metric subsection. The SC has a partnering relation with 8 RSPs to recover the modules from returns and enhance quality to make them suitable for re-manufactured product.

4.1 Model Solution Procedure (Algorithm)

As is evident, the formulated model is a bi-objective one, and the model objectives are conflicting to each other. Considering that the epsilon constraint or efficient frontier-based solution procedure has been popular and recommended in the literature (Rardin, 1988) to solve bi-objective models for obtaining good solutions, this research utilizes the epsilon constraint approach following the steps listed below to obtain efficient frontier solutions.

Step 1. minimize *SUS*, objective function 1

Step 1.1 subject to (s.t) all constraints and model equations not considering objective function 2 for maximizing *Profit* in equation (11), but using equation (12) to compute *Profit*

Step 2. maximize *Profit*

Step 2.1 subject to all constraints and model equations not considering objective function 1 for minimizing *SUS* defined in equations (4), but using equation (4.a) to compute *SUS*.

Step 3. maximize *Profit*, s.t. description in Step 2.1 and including a new constraint SUS ≤ s-target. (s-target is the target *SUS* value to be computed by inserting a constraint *SUS ≤ s-target* (say equation 4.b) during solving). Detailed procedure, including examples to obtain s-target and obtaining solutions following all the steps in the algorithm is described in Model Solutions Following the Algorithm to follow.

A flow chart for the algorithm steps is also shown in the appendix. Continue to solve Step 3 for a planned number times. Model solutions following above algorithm are presented in Tables 8, 10, and 11 under three considerations to follow.

Illustration on Integration of Sustainability Metrics

Prior to illustrating solutions in Tables 8, 10, and 11, it is important to study the way the model integrates sustainability metrics in obtaining each of the solutions.

Supplier management: As discussed before, the SC monitors and evaluates the supplier's sustainability performances based on their average scores in the QS metrics, as detailed in the APPENDIX document. **Table 4** presents typical sustainability performance metrics for suppliers. For example, Supplier 1 has the highest performance score of 1 for metric QS7. For each solution in the algorithm, the model first takes into account the supplier sustainability metrics score *QS*1 to *QS*7 given in **Table 4**, to evaluate the supplier's overall sustainability performance to identify qualified suppliers following equation (1) and integrates the solution for subsequent decision process for assigning orders to them.

In this qualified supplier affiliation process, the model considered a qualifying minimum score, *TQS* (in equation 1) = 0.8, as set by the SC , considering an average expected score by a supplier for each metric close to 0.97 (0.97^7≈0.8). The model identified the following suppliers as qualified out of the 9 suppliers of SC: [1, 2,3,4,5, 8 and 9].

Production management: **Table 5** presents sustainability performance metrics for the plants. Detailed definitions of these plant sustainability metrics are described in the APPENDIX document. The SC evaluates sustainability performance of their production plants considering last year's operations data.

Table 2 Product demand and marketing plan.

	Average Demand	Planned Marketing	
Product	D_p units	New product (d_{pt}, t=1) units	Re-manufactured (d_{pt}, t=2) units
1	4,629	2,315	2,777
2	9,385	4,693	5,631
3	7,269	3,635	4,361
4	8,645	4,323	5,187
5	6,757	3,379	4,054

Following equation (2), overall average score for the eight-metrics given in **Table 5** is compared with the set qualifying score *ES* (equation (2)) for identifying sustainability and quality capable of production plants. The SC sets such qualifying score to be 0.79 by considering expected performance score ≈0.97 for each metric and overall performance for eight metrics (0.97^8≈0.79). The model identified the following five production plants as qualified out of the 6 plants of SC: [2, 3, 4, 5, and 6] and integrated this decision for subsequent decisions to assign production.

Recovery of modules from customer returns: Taking a similar approach for qualification criteria relevant to supplier and production plants, the SC identifies qualified RSPs out of their 8 enlisted RSPs to assign recovery orders to obtain recovered and quality enhanced modules from customer returns to produce re-manufactured products. The SC evaluates the RSPs following seven sustainability performance metrics, RS1 to RS7, which are similar to QS1 to QS7 for supplier sustainability performances as defined in detail in the APPENDIX document. The model considers overall score by a RSP based on **Table 6** data for identifying qualified RSPs using equation (3) and a minimum qualifying overall sustainability metric score of *VC*= 0.77 for RSPs. *VC* is set by the SC by considering expected performance score for each metric to be RS≈0.965 and the overall sustainability performance metric score for the seven metrics (0.965^7=0.77). Out of 8 RSPs, the model identified the following RSPs to be qualified [1, 2,3,5,6, 7, 8] and integrated this decision of qualified RSPs for subsequent assignment of recovery work.

The objective of the SC is to improve environmental, economic, and social sustainability performance by considering reference-benchmarked performance of superior performing companies as targets. These benchmarked target values and their comparison with metrics for SC functions are presented in **Table 7**. **Table 7** presents current sustainability performance metrics for a typical supplier, plant, *RSP*, and training category, along with target/benchmarked performance metrics value set by the SC. As such, there are gaps in most of the cases. For example, score for supply sustainability metric 1(QS1) for supplier 1 is 0.99 and the target is 1. In addition to the above, the SC collected information from customer surveys and various superior performing companies, and considered demand growth potential *GR*(*d*) values to vary according to a uniform distribution between 5% and 15% , denoted by U(0.5 ; 0.15). Growth effect due to supply GR(*s*); production (GR(*j*); recovery (GR(*v*), and training GR(*g*) assumed to be 0.25% of average *GR*(*d*). As discussed above, such a value of *GR*(*d*) is achievable based on performance improvement to close the performance gap for gp_i relevant to SC function *i*, where $i \in I^s$ for supply, $i \in I^j$ for production , and $i \in I^v$ for remanufacturing, and $i \in I^g$ for training management functions (see equation (7)).

The SC similarly considered the cost reduction values for production *RE*(*j*), $j \in I^j$ to be: U(0.05, 0.08); supply cost reduction *RE*(*s*), $s \in I^s$ for new module *NM*(*S*) to be: U(0.05, 0.10); and recovered module cost reduction *RE*(v), $v \in I^v$, to be: U(0.03, 0.07). Such assumptions in cost reductions are reasonable and may always be modified for specific situations.

Table 4 Suppliers sustainability metrics data.

	Supplier Sustainability Metric (QS) Values						
Suppliers	**QS1**	**QS2**	**QS3**	**QS4**	**QS5**	**QS6**	**QS7**
1	0.99	0.99	0.98	0.93	0.96	0.95	1
2	0.98	0.99	0.97	0.94	0.98	0.94	0.99
3	0.98	0.98	0.98	0.93	0.99	0.94	0.99
4	1	0.99	0.97	0.95	0.98	0.93	0.98
5	0.98	0.99	0.98	0.94	0.98	0.95	0.98
6	0.96	0.97	0.96	0.95	0.97	0.94	0.97

Table 5 Production plant sustainability metric data.

	Plant sustainability metric values							
Plants	**PS1**	**PS2**	**PS3**	**PS4**	**PS5**	**PS6**	**PS7**	**PS8**
1	0.95	0.96	0.98	0.97	0.92	0.95	0.96	0.99
2	0.97	0.97	0.97	0.98	0.94	0.99	0.99	0.96
3	0.96	0.97	0.98	0.97	0.93	1	0.96	1
4	0.97	0.98	0.99	0.96	0.95	0.99	0.99	0.95

	Plant sustainability metric values							
Plants	**PS1**	**PS2**	**PS3**	**PS4**	**PS5**	**PS6**	**PS7**	**PS8**
5	0.95	0.98	0.98	0.97	0.95	1	0.96	0.99
6	0.95	0.97	0.98	0.97	0.94	1	1	0.98

Table 6 Typical sustainability metric for RSP.

	Values for the RSP's Sustainability Metrics (RS)						
RSP	**RS1**	**RS2**	**RS3**	**RS4**	**RS5**	**RS6**	**RS7**
1	0.96	0.97	1	0.94	0.99	0.95	0.96
2	0.97	0.98	0.98	0.93	0.98	0.95	0.97
3	0.98	0.99	0.98	0.95	0.97	0.94	0.99
4	1	0.98	0.96	0.93	0.97	0.93	0.96
5	1	0.98	0.97	0.93	0.99	0.93	0.99

Table 7 Comparison of sustainability metrics for typical supplier, plant, RSP, and engagement training with benchmarked performance set by SC.

	Scores for Supplier Sustainability Metrics (QS)							
	QS1	**QS2**	**QS3**	**QS4**	**QS5**	**QS6**	**QS7**	
Supplier1	0.99	0.99	0.98	0.93	0.96	0.95	1	
Supplier2	0.98	0.99	0.97	0.94	0.98	0.94	0.99	
Benchmarked /target	1	1	1	0.98	1	0.99	1	
	Scores for Plant Sustainability Metrics (PS)							
	PS1	**PS2**	**PS3**	**PS4**	**PS5**	**PS6**	**PS7**	**PS8**
Plant1	0.95	0.97	0.97	0.98	0.92	0.99	0.99	0.96
Plant2	0.97	0.97	0.97	0.98	0.94	0.99	0.99	0.96
Benchmarked/target	0.98	1	1	1	0.98	1	1	1
	Scores for RSP's Sustainability Metrics (RS)							
	RS1	**RS2**	**RS3**	**RS4**	**RS5**	**RS6**	**RS7**	
RSP1	0.96	0.97	1	0.94	0.99	0.95	0.96	
RSP2	0.97	0.98	0.98	0.93	0.98	0.95	0.97	
Benchmarked/target	1	1	1	0.98	1	0.99	1	

	% Of Community College Graduates in Training Category				
	1	2	3	4	5
Current coverage	18	18	23	30	23
Target	20	20	25	30	25

Table 8 Model solutions for sustainability performance vs profit when demand growth benefits are considered.

Solutions	$SUS = gp_s + gp_j + gp_v + gp_g$	*GR*(d)	Profit in $M	Revenue in $M	Total cost in $M	Definitions for Model
1	0.847	0.079	2.24	11.64	9.4	*min SUS*
2	2.57	0.04	2.75	11.17	8.43	*max Profit*
3	2.23	0.044	2.74	11.26	8.52	max *Profit* s.t. *SUS*≤ 2.23
4	1.89	0.053	2.73	11.36	8.63	max *Profit* s.t. *SUS* ≤1.89
5	1.55	0.061	2.69	11.44	8.75	max *Profit* s.t *SUS* ≤ 1.55
6	1.21	0.07	2.63	11.54	8.91	*max Profit* s.t *SUS* ≤ 1.21
7	0.847	0.079	2.49	11.64	9.15	*max Profit* s.t *SUS* ≤ 0.847

Table 8.a Details for model solution in Table 8.

Solutions	*SUS*	gp_s, gp_j, gp_v, gp_g	GR(d)	Total cost In $M	Components for Total Cost in $M					
					PRC	*SPC*	*RMC*	*EGC*	*EMC*	*SSC*
1	0.847	0.341,0.199,0.267,0.04	0.079	9.4	3.12	4.21	1.89	0.118	0.041	0.042
2	2.57	1.18,0.92,0.39,0.08	0.04	8.43	2.8	3.69	1.77	0.113	0.033	0.017
3	2.23	0.995,0.828,0.327,0.080	0.044	8.52	2.83	3.74	1.79	0.114	0.033	0.017
4	1.89	0.770,0.738,0.302,0.80	0.053	8.63	2.87	3.81	1.79	0.114	0.034	0.017
5	1.55	0.585.0.612,0.283,0.080	0.061	8.75	2.91	3.87	1.8	0.116	0.034	0.017
6	1.21	0.43,0.43,0.27,0.08	0.07	8.91	2.98	3.94	1.81	0.116	0.034	0.017
7	0.847	0.341,0.199,0.267,0.40	0.079	9.15	3.12	4.02	1.82	0.117	0.034	0.042

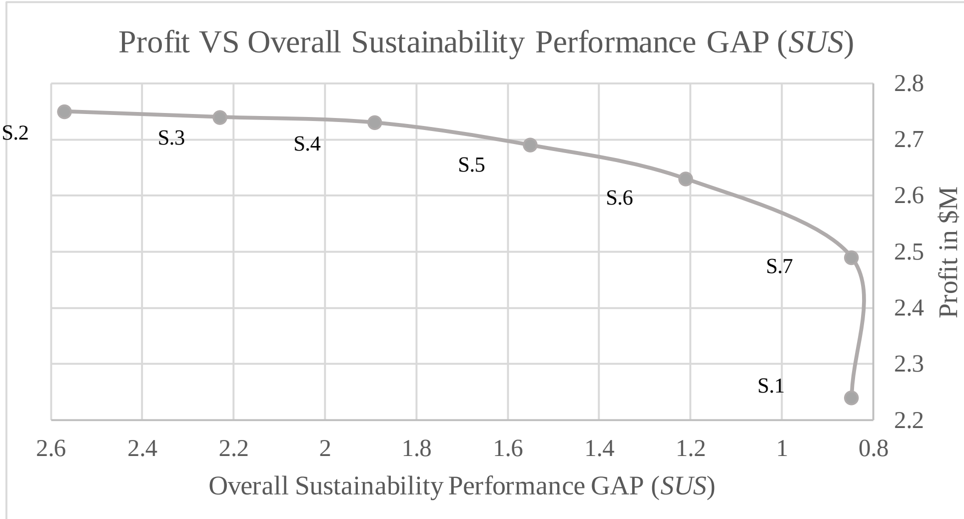

Figure 2 Profit vs sustainability performance gap (*SUS*) based on results in Table 8.

4.2 Model Solutions Following the Algorithm

Table 8 presents seven model solutions as defined in the last column of the Table. These Sustainability Performance*s vs* Profit based efficient frontier solutions considered anticipated demand growth due to improvement of sustainability performances based on the criteria discussed above. Solution 1 minimizes *SUS* following step 1; Solution 2 maximizes profit according to Step 2, and Solutions 2 to 7 followed Step 3 of the solution algorithm described above. To decide on the number of solutions and *s-target* for the solutions, the following procedure was followed:

The minimum obtainable or best value for overall sustainability performance gap *SUS* is 0.847 (from Solution 1. Step 1 of algorithm) and the maximum or worst sustainability performance gap is *SUS* =2.57 obtained from Step 2 (maximize profit): leading to a difference of (2.57 - 0.847) = 1.7. Five intervals/solutions are planned for this problem, to have a reasonable value of 1.7/5= 0.34 for each (see the components of *SUS* also in **Table 8.a**). Solution 2 has the lowest cost $ 8.43M (**Table 8**). It did not obtain much demand growth by not minimizing gp_s, gp_j ,gp_v, and ;gp_g. The achieved minimum demand growth of 4.0% was needed to ensure a revenue $11.17 M to maximize profit.

For Solutions 2 to 7, profit gradually decreased to $2.49 M (for Solution 7) with a total decrement of $0.26 M as the sustainability performance improved with the decrement of *SUS* value from 2.57 to 0.847, as may be seen in **Table 8**. The trend is depicted in **Figure 2**(Solution numbers are shown as S.1, S.2….).

It may be mentioned here that Solutions 3 to 7 are non–dominated or efficient frontier solutions. Solution 1(S.1,) and interval (this gap may be any other value by taking more or less number of intervals). Hence, the ***s-targets*** will be: 2.57 - 0.34 = 2.23 (solution 3); 2.23-0.34=1.89 (solution 4) ; and so forth.

To illustrate the solutions, for example, Solution 1 with the lowest value of *SUS* could obtain the highest possible demand growth of 7.9% and a lowest possible revenue of $11.64 M, with a profit of $2.24M. Solution 1 needed to include several improvement options (Refer to **Table 9** and related analysis to follow) to obtain lowest possible gaps for gp_s (supply), gp_j (production), gp_v (remanufacturing) and gp_g(training), (see Table 8.a). As expected, Solution 1 does not take into consideration the cost or profit implications. But, due to incorporation of improvement steps, the effects on costs and profit are obvious. As such, profit for Solution 1 is the lowest and total cost is the highest. As expected, profit for Solution 2 is the highest at $2.75M with an *SUS* value of 2.57, the highest of overall sustainability performance gap

2(S.2) are also shown in the figure. Since solution 1(S.1) does not consider profit or cost implications (with the only objective to improve *SUS*), and S.2 does not consider *SUS* requirements. S.1 and S.2 may not be considered as the non-dominated solutions.

A user cannot obtain a best value for both the objectives for such solutions. These solutions may be called as compromise or trade-off solutions. Value for one of the objectives becomes better at the expense of the other. Such solutions are selected by a user based on the importance imparted by the user to one objective with a reasonable trade-off value for other. For example, if the user would like to obtain a maximum profit as possible by achieving reasonable sustainability performance *SUS* around 1.6, then Solution 5 should be the choice.

Table 9 presents model decisions on selection of improvement options to close the gaps gp_s, gp_j, gp_v, gp_g to minimize *SUS* for Solution 1 presented in **Table 8** and **Table 8.a**. At the existing condition, values of gaps computed by the model for gp_s, gp_j, gp_v, gp_g are {1.21, 0.92, 1.05, and 0.08**}.**

To illustrate how the existing gaps were computed by the model: based on equation (5) without an improvement option ($\sum_{o \in O} PI_{ieo} w_{ieo} = 0$), a part of gp_i =only for supply function $i \in I^s$ $s \in I^s$ (taking s=1, for supplier 1);

$$gp_{s=1} = \sum_{e \in E^q; q \in E^q} (BS_{s=1,e} - GS_{s=1,e}), \forall i \in I^s, s \in I^s, s = 1$$

performance metric $e \in E^q$, $q \in E^q$ = (QS 1,….QS7), (see the supply management sustainability subsection, just to illustrate for supplier 1 $gp_{s=1}$: (1 - 0.99) + (1 - 0.99) + (1 - 0.98) + (0.98 - 0.93) + (1 - 0.96) + (0.99-0.95) + (1 - 1) = 0.17 (see values for *QS*1 to *QS*7 values for Supplier 1 and the benchmarked target values as presented in **Table 7** . For Solution 1 in **Table 8** and 8.a., the model selected improvement options (5,5,6, 6,1 and 2) for metrics QS1, QS2, QS3, QS4, QS5 and QS6 respectively, to minimize gaps by {0.01, 0.009, 0.02, 0.033, 0.034, 0.035} for Suppliers, respectively, for the example, based on **Table 9**. As such, total gap reduced by 0.141, which makes the *GS* value for Supplier 1 in equation (5) from 0.17 to (0.17 - 0.141) = 0.029; the model did not select improvement options for QS7 for Supplier 1 since its performance is equal to the target.

Table 9 similarly presents typical *improvement options* and *degree of improvement* obtained for *PS* metrics applicable to plants, and *RS* metrics for applicable to RSPs. Similar illustrations for reduction of gaps can be given taking typical existing values for *PS* and *RS* metrics and their benchmarked targets, from **Table 7**, and model decisions on improvement options and improvement values as found from **Table 9**. **Table 9** also presents that Solution 1 in **Table 8**, spent $179,568 for including improvement options to minimize overall gap of gp_s from 1.18 to 0.341; spent $205,902 for including improvement options to minimize overall gap gp_j from 0.92 to 0.199; spent $53,736 for including improvement options to minimize overall gap gp_v from 0.39 to 0.267.

Table 10 presents seven solutions with similar definitions as in **Table 8**. But, these solutions considered *anticipated cost reductions* in addition to *demand growth* to be obtained from the *sustainability performance improvement effect*. As may be observed in **Table 10**, Solution 1 for minimization of *SUS* obtained the same objective value of 0.847 for *SUS* but profit for this solution is $2.71 M (higher than that of Solution 1 in **Table 8**) and the total cost of $8.93 M is lower than $9.4 M (in **Table 8**), with revenue being the same as in Solution 1, **Table 8**. For Solution 1, the model assigned new module orders to suppliers, recovery orders to RSPs, and allocated production to plants just to fulfill demand which are imposed by constraints (23), (25), and (27) but not based on cost because Objective 2, equation (11) does not come into play. After fulfilling demand, the model tries to apply improvement options using constraints (5) and (6) for supply, production, recovery and training, without considering cost. But, some cost benefits come automatically, as gaps decreased, demand growth happens based on equation (7) which ultimately could reduce some costs for supply, recovery, production and training based on model equations (8), (9), and (10). The intricate interrelationships between demand and cost functions and achievement of gap levels in sustainability functions have an impact on the solutions. Solution 2 for maximization of profit obtained $2.94 M profit (**Table 10**), which is higher than $2.75M (in **Table 8**) and an improved sustainability performance *SUS* value to 1.149 (**Table 10**) compared to 2.57 in **Table 8**. Solution details for each gap gp_s, gp_j, gp_v and gp_g and cost components are shown in **Table 10.a**. Although the objective of Solution 2 was to maximize profit, this solution was motivated to improve *SUS* to obtain a demand growth of 7.1% (compared to 4.0% in **Table 8**) and to take advantage of cost reductions and to boost profit by improving revenue to $11.56M (**Table 9**, Solution 2), from a previous value of $11.17M (**Table 7**, Solution 2) with some cost increase. A similar approach as in **Table 8** solutions have been taken here also to set *s-targets*. For Solutions 3 to 7, a similar decreasing trend of profit and increasing trend of cost may be observed in **Table 10** too.

Table 9 Model output on selected sustainability metrics improvement options (gap reduction) to minimize gaps gp_s, gp_j, gp_v and gp_g in Solution 1 of Table 7.

gp_s Improved to 0.341, Total Expenses for Minimizing gap gp_s: $179,568							
Typical Supplier	Typical Selected gp_s reduction options related to metrics QS1 to QS7 and (obtained reduction of gap).						
	QS1	QS2	QS3	QS4	QS5	QS6	QS7
1	5 (0.01)	5 (0.009)	6 (0.02)	6 (0.033)	1 (0.034)	2 (0.035)	
2	5(0.014)		4 (0.03)	6 (0.034)	5 (0.014)	4 (.03)	
3	3 (0.017)	2 (0.007)	2 (0.02)	3 (0.016)		5 (0.026)	

gp_j Improved to 0.199, Total Expenses for Minimizing Gap gp_j :$205,092								
	Model output for gp_l reduction options related to metrics PS1 to PS8 and (obtained reduction of gap).							
Plant	PS1	PS2	PS3	PS4	PS5	PS6	PS7	PS8
2	5(0.009)	4(0.027)	1(.029)	6(.018)	1(.021)		3(0.009)	2(.033)
3	4(0.017)	4(.024)	1(0.02)	4(0.019)	3(.025)		2(0.035)	0

4	1 (0.009)	6(.018)	6(.006)	3(0.033)	2(0.026)		3(0.005)	2(0.032)

gp_v improved to 0.267, Total expenses for minimizing Gap gp_v :$53,736							
	Model output for gp_v reduction options related to metrics RS1 to RS8 and (obtained reduction of gap).						
RSP	RS1	RS2	RS3	RS4	RS5	RS6	RS7
1	3(0.03)	5(0.028)		1(0.033)	3(0.01)	3(0.025)	3(0.028)
2	6(0.028)	6(0.017)	6(0.017)	3(0.023)	4(0.02)	3(0.02)	4(0.02)
3	1(0.015)	1(0.009)	3(0.02)	5(0.03)	3(0.03)	5(0.031)	

Table 10 Model solutions for sustainability performance vs profit when demand growth and cost reduction benefits are considered.

Solutions	$SUS= gp_s+ gp_j +gp_v+gp_g$	$GR(d)$	Profit in $M	Revenue in $M	Total cost in $M	Definitions for Model
1	0.847	0.079	2.71	11.64	8.93	min SUS
2	1.149	0.071	2.94	11.56	8.62	max Profit
3	1.087	0.073	2.93	11.57	8.64	max Profit s.t SUS≤ 1.087
4	1.029	0.074	2.93	11.59	8.66	max Profit s.t SUS≤ 1.029
5	0.969	0.076	2.93	11.61	8.68	max Profit s.t SUS≤ 0.969
6	0.909	0.077	2.91	11.62	8.71	max Profit s.t SUS ≤0.909
7	0.847	0.079	2.87	11.64	8.77	max Profit s.t SUS ≤0.847

Table 10.a Details for model solution in Table 10.

Solutions	SUS	gp_s, gp_j, gp_v, gp_g	Gr(d)	Total Cost	Components for Total Cost in $M					
				$M	PRC	SPC	RMC	EGC	EMC	SSC
1	0.847	0.341,0.199,0.267,0.04	0.079	8.93	2.99	3.83	1.90	0.127	0.044	0.042
2	1.149	0.458,0.284,0.327,0.08	0.71	8.62	2.94	3.73	1.78	0.117	0.034	0.017
3	1.087	0.431,0.263,0.313,0.08	0.073	8.64	2.95	3.74	1.79	0.117	0.034	0.017
4	1.029	0.401,0.246,0.302,0.08	0.074	8.66	2.95	3.75	1.784	0.117	0.034	0.017
5	0.969	0.379,0.242,0.268,0.08	0.076	8.68	2.952	3.77	1.79	0.117	0.034	0.017
6	0.909	0.345,0.216,0.268,0.08	0.077	8.71	2.97	3.78	1.793	0.117	0.034	0.017
7	0.847	0.341,0.199,0.267,0.04	0.079	8.77	3.00	3.79	1.79	0.117	0.034	0.041

For these solutions in **Table 10**, profit decrement is $(2.94-2.87) M=$ 0.07 M (for Solutions 2 to 7) compared to $0.26M in **Table 8**. A total cost increase $(8.77-8.62) M= $0.15 M (**Table 10**) is also quite small with the improvement of sustainability performance by decreasing *SUS* value from 1.149 to 0.847. Such trend differences from **Table 10** solutions may also be visible from **Figure 3**. Characteristics for Solutions 3 to 7 are similar to **Figure 2**. These are also non-dominated trade- off solutions as described before. Comments on Solution 1 are similar to that in **Figure 2**. **Table 11** presents non-dominated or efficient frontier model solutions for sustainability performances vs profit *without considering any benefit* on business performance from improvement of sustainability performance.

Based on **Table 11**, with the improvement in sustainability performances by reducing overall sustainability metrics gap *SUS* from 3.26 (Solution 2) to 0.847 (Solution 7) , profit decreases from $2.65M to $2.20 M, and total cost increases from $8.14 M to $8.59 M. For these solutions, the model equations (7), (8), (9), and (10) are not applicable, since these equations are formulated to take into account the benefits from sustainability performance improvement in terms of demand growth and cost reductions.

Compared to solutions in **Tables 8** and 10, these solutions in **Table 11** generated lower revenue and profit for each solution. As expected, since no anticipated benefits due to improvement of sustainability performance have been taken into consideration, business performance deteriorated.

The solutions are defined in the last column of the Table. This table includes 7 solutions, of which Solution 1 minimizes *SUS*, and Solution 2 maximizes Profit. Solutions 3 to 7 are solved following steps 3 of the solution algorithm, similar to the solutions in Tables 8 and 9. *S-targets* for Solutions 3 to 7 have been computed by considering lowest value of *SUS* of 0.847 (highest sustainability performance) for Solution 1 and the highest *SUS* value 3.26 (lowest sustainability performance) for Solution 2.

Although, business outcomes similar to solutions in **Table 11** (see also details in **Table 11.a**) for a SC that pursues sustainable practices are unusual, these solutions provide *managerial insights* on the *cost implications* and *benefits* when compared with **Tables 8** and 10. These outcomes are unusual because when organizations invest in sustainability improvement steps, improvement in customer impression is almost obvious, which will provide them business growth, cost reduction and ultimately an improvement in profit (see Guide and Wassenhove, 2003; Govindan, 2016, Zhu et al., 2008).

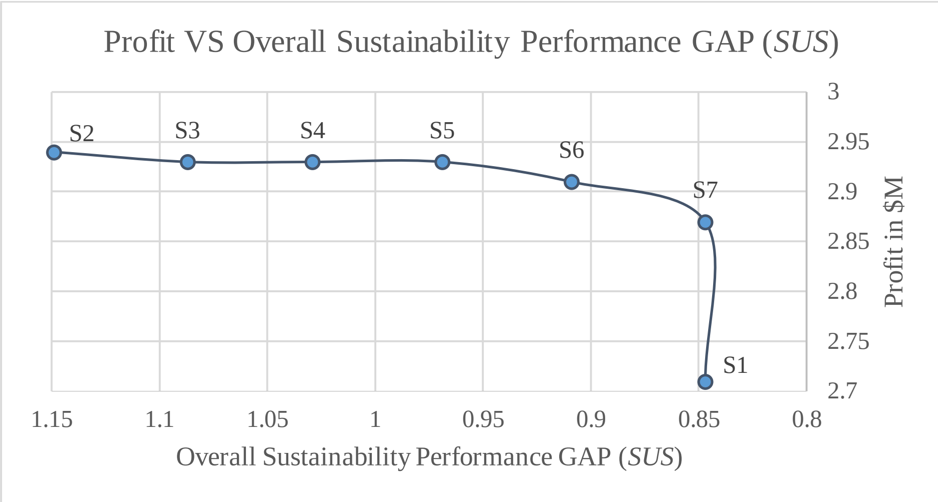

Figure 3 Sustainability performance SUS vs profit based on Table 9.

Table 11 Model solutions for sustainability performance vs profit not considering any benefit from sustainability performance improvement.

Solutions	$SUS = gp_s + gp_j + gp_v + gp_g$	Profit in $M	Revenue in $M	Total Cost in $M	Definitions for Model
1	0.847	1.87	10.79	8.92	Min SUS
2	3.26	2.65	10.79	8.14	Max Profit
3	2.78	2.63	10.79	8.16	max Profit s.t SUS ≤ 2.78
4	2.3	2.58	10.79	8.21	max Profit s.t SUS ≤ 2.3
5	1.82	2.52	10.79	8.27	max Profit s.t SUS ≤ 1.82
6	1.34	2.41	10.79	8.38	max Profit s.t SUS ≤ 1.34
7	0.847	2.20	10.79	8.59	max Profit s.t SUS ≤ 0.847

Table 11.a Details for model solution in Table 10.

Solutions	SUS	gp_s, gp_j, gp_v, gp_g	Total cost in $M	Components for Total Cost in $M					
				PRC	SPC	RMC	EGC	EMC	SSC
1	0.847	0.341,0.199,0.267,0.04	8.92	2.91	4.02	1.8	0.11	0.035	0.042
2	3.26	1.21,0.92,1.05,0.08	8.14	2.7	3.56	1.72	0.109	0.032	0.017
3	2.78	1.21,0.92,0.57,0.08	8.16	2.7	3.56	1.74	0.109	0.032	0.017
4	2.3	1.022,0.585,0.343,0.80	8.21	2.71	3.58	1.76	0.109	0.032	0.017
5	1.82	0.75,0.682,0.308,0.08	8.27	2.73	3.62	1.76	0.109	0.032	0.017
6	1.34	0.465,0.521,0.274,0.8	8.38	2.77	3.69	1.76	0.109	0.032	0.017
7	0.847	0.341,0.199,0.267,0.04	8.59	2.9	3.74	1.77	0.109	0.032	0.042

Based on the above analysis of model solutions, it is apparent that the presented model and the selected overall approach can be used to *effectively design and plan a SC by integrating sustainability metrics* for improving its overall performances. These are some the key features of the proposed model to make effective decisions, that distinguish it from prior research.

In addition to the above discussion, a detailed analysis on SC performance improvement has been included in the APPENDIX to provide more insights to SC managers, when demand growth and cost improvement varies, compared to what has been considered in the above solutions.

5. DISCUSSION AND CONCLUSIONS

The research introduced a model based SC design and planning approach for overall performance improvement of a business by integrating environmental, economic, and social sustainability metrics. It identified sustainability factors and applicable measures for each SC function following the guidelines in the literature and formulated them mathematically to integrate with the planning model. Such formulations will *facilitate SC managers* to include quantitative control levers to develop a *successful business plan*. The model chosen and illustration of model solutions also provide insights to *select trade-off solutions* based on their *own unique business situations.*

The model includes an overall SC planning to design the product incorporating a modular architecture, management of new module procurement, recovery of modules from customer returns, and production of new and re-manufactured product. It includes insights to improve sustainability metrics, reduce relevant costs and contributions, in addition to planning for collection of customer returns, overall product mix and select social responsibility. The research created a framework for future studies by including uncertainties in demand, collection, and quality of returns.

Several business decisions are implicit in the study for improving business growth, environmental performance image, and economic performance. The study provides several options to SC managers to *operate the business* with various *controlling options* based on targeted *performances* to achieve overall business objectives. Since it is a *target-based planning* for *several metrics*, SC management may take advantage of *pursuing phased actions* to achieve their objectives over several periods of years. Consideration of multiple criteria creates the scope of *prioritizing subsets of metrics* to select trade-off options. The approach further includes *improving corporate responsibility* by organizing community based training, which in turn provides the advantage of obtaining skilled manpower for their own recruitment. Since performances are measured in terms of ratio and gap relative to a benchmarked company, the business can monitor and compare the performances of its internal operations and *prioritize action plans* for taking improvement measures.

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APPENDIX

Notations

Indices

P set of products, indexed by $p\in P$
T types of product (new, re-manufactured) or modules (new, recovered), indexed by $t\in T$
I set of SC functions (supply, production, and recovery management), indexed as $i\in I$
I^j set of plants, indexed by $j\in I^j$
I^v set of RSPs, indexed by $v\in I^v$
I^s set of suppliers, indexed by $s\in I^s$
I^g set of training categories, indexed as $g\in I^g$
I^j I^s,I^v , I^g are partitions of I
M set of modules, indexed by $m\in M$
E set of sustainability performance metrics, indexed by $e\in E$
E^n set of sustainability performance metrics for production management, indexed by $n\in E^n$
E^q set of sustainability performance metrics for supply management, indexed by $q\in E^q$
$E^{q'}$ set of sustainability performance metrics for recovery management, indexed by $q'\in E^{q'}$
E^τ set of sustainability performance metric for training management, indexed by $\tau\in E^\tau$
E^n, E^q, $E^{q'}$, E^τ are the partitions of E
C set of components, indexed by $c\in C$
O set of options for improving sustainability performances, indexed as $o\in O$
Such options in production includes: better technology to become energy efficient, and to have higher reliability for production and higher quality; better manufacturing system, such as cellular manufacturing to have better flow or production rate, quality, and lower inventory; condition based and Total Productive Maintenance(TPM) to get higher OEE(overall equipment effectiveness); subcontracting production to network partners that have suitable technology plant for improved quality, reliability, energy consumption and emission generation; using alternative raw materials, and using better production methods. Similar options are applicable to supply, and recovery management also.

Parameters

BP_{ie} : benchmarked sustainability metric e ($e\in E$) for SC function i ($i\in I$).
GS_{ie} : current sustainability performance metric e ($e\in E$) for SC function i ($i\in I$).
CZ_{ms} : cost of module m from supplier $s\in I^s$ (\$).
CR_{mv} : cost of recovered module m by RSP $v\in I^v$ (\$).
CCR_p : cost of collecting customer returns for product p through retailer (this cost includes incentives paid to customer, cost of collection, and storing of returns) (\$).
CP_{pt} : cost of producing product p of type t (\$).
D_p : average demand of product p considering all types (units).
DD_j : average distance for distributing product from plant j to retailers in market, (miles).
d_{pt} : average demand of product p of type t (units).
EC_{pt} : effective production cost for product p of type t after cost reduction due to improving production sustainability performance (\$).
EEP_p : energy spent for producing product p (kWh).
EES_{ms} : energy spent for producing module m by supplier s (kWh)
EER_{mv} : energy spent in for recovery and quality enhancement of module m by RSP v (kWh).
ECR_{mv} : effective recovery cost for module m from returns by RSP v after considering cost reduction due to recovery sustainability performance improvement (\$).
ECZ_{ms} : effective supply cost for a new module m by supplier s after considering cost reduction due to sustainability performance improvement (\$).
EMP_p : generation of harmful emissions for producing product p (in equivalent kg of CO_2).
EMS_{ms} : generation of harmful emissions for producing module m by supplier s (in equivalent kg of CO_2).
EMR_{mv} : generation of harmful emissions for recovery and quality *enhancement* of module m from returns of RSP v (in equivalent kg of CO_2).
ES : qualifying score for manufacturing plant to be assigned production.
FE : average per mile fuel energy in MJ converted to kWh used by a standard semi-trailer truck load according to US Department of Transportation data
FM : average per mile generation of harmful emissions in equivalent kg of CO_2 by a standard semi-trailer truck load according to US Department of Transportation data
FRC_{mv} : fixed cost for ordering recovery of module m to RSP v (\$)
FPC_j : fixed setup cost for producing product in plant j (\$).
FPI_{ieo} : fixed cost for implementing option o for improving production sustainability metric $e\in E^n$ in plant $i\in I^j$ (\$).
FSC_{ms} : fixed cost for ordering new module m to supplier s (\$)
FSI_{ieo} : fixed cost for installing option o for improving sustainability metric $e\in E^q$ for supplier $i\in I^s$ (\$)

FRI_{ieo} : fixed cost for installing option o for improving recovery metric $e \in E^{q,'}$ for RSP $i \in I^{v}$ ($).
FTI_{ieo} : fixed cost for including option o for improving training sustainability metric enrollment of trainee $e \in E^{\tau}$ in training category $i \in I^{g}$ ($)
$GR(d)$: % of demand growth by reducing sustainability metric gap with benchmarked level
$GR(i)$, : % of demand growth effect by reducing sustainability metric gap in SC function i (supply, production, and recovery management) with benchmarked level
nx : % of average demand D_p for new product p
PI_{ieo} : performance improvement obtainable for SC function i ($i \in I$) for sustainability metric e ($e \in E$) through option o
PP_{jn} : score obtained by plant j for sustainability metric $n \in E^{n}$
$RR_{vq'}$: score obtained by RSP v for recovery sustainability metric $q' \in E^{q'}$
RE (i) : cost reduction by SC function i by improving sustainability performance. The cost *reduction* is assumed to follows a uniform distribution U (cl, ch).
rx : % of average demand D_p for re-manufactured product p.
SP_{sq} : score for sustainability metric $q \in E^{q}$ by supplier s.
STL_p : amount of product p for standard semi-trailer truck load
TI_g : cost for providing training in category g for each trainee ($).
$nEd_{g\tau}$: number of enrolled community college trainee/student τ (sustainability performance measure) in category g as a % total community college students.
TQS : qualifying score for a supplier to supply new modules for the tracked QS metrics
VC : qualifying score for a RSP to get order for recovery of modules.
VP_{pt} : the market price for product p of type t ($)
ρ_{pm} : number of module m used to produce product p (units)
BN : $BN1$, $BN3$, a big number

Decision Variables

gp_i : sustainability performance gap in SC function i ($i \in I$) compared to benchmarked performance
ed_{pt} : effective demand of product p of type t (units)
RS_v : 1, if RSP v qualifies to supply recovered module; 0 otherwise.
x_{pjt} : amount of product p of type t manufactured in plant j
rz_{mv} : 1, if recovered module m is supplied by RSP v; 0 otherwise
w_{ieo} :1, if option o is selected to improve sustainability performance $e \in E$ for SC function i; 0 otherwise
AS_s : 1, if supplier s qualifies to supply module; 0 otherwise
PC_j : 1, if plant j fulfills quality and sustainability criteria to produce a product; 0 otherwise
z_{ms} : number of new module m supplied by suppliers s

QS Metrics Used in this Research for Evaluating Sustainability Performance of Suppliers

The QS metrics are ratios, and as such do not have units.

QS1: Supplied Module Quality, defined as AQP (Acceptable Quality Percentage, computed as: (1- rejection rate). The lowest AQP value is the metric here considering all the modules in the consignments supplied during the last interval.

QS2: Quantity and delivery variation measured as: 1- total % discrepancies from the contractual quantity and lead time in the case of delivery. Here also, the lowest value is the metric based on performance in the consignments supplied in the last interval for each item.

QS3: Flexibility in accommodating change request for quantity, delivery schedule, item specifications, design #; transportation mode and similar issues; measure is % of change requests accommodated during last interval.

QS4: Lowest OEE of supplier's production equipment as a % of Target OEE according to contract.

QS5: OSHA performance $\equiv$ 1 - (% non-compliance OSHA requirements for the last quarter).

QS6: Reduction in per product energy consumption and generation of harmful emission as a % of target value for these according to contract, lowest one is the measure for evaluation. It also related to compliance to regulatory requirements

QS7: Employee turnover, 1- (% turnover).

PS Metrics Used in this Research for Evaluating Sustainability and Quality Capability of Production Plants. Like QS metrics**,** the PS metrics are also ratios.

PS1: average plant availability based on one year record;

PS2: average AQP for production by a plant;

PS3: process capability metric as a ratio of plant's average obtained process capability performance with target capability 2 (Cpk value for a six sigma company);

PS4: OSHA compliance % and ratio of accident free days, the metric is the lower of the two;

PS5: Reduction in the ratio of per product energy consumption and harmful emission in equivalent kg of CO_2 from the SC plant with the ideal or target values for such product, the lower one is the metric; also related to compliance to regulatory requirements

PS6: 1 **-** (% *employee turnover*);

PS7: ratio of the number of improvement suggestions implemented out of improvement suggestions given by the employees;

PS8: % of participation by the overall employees in training sessions on emergency handling, lean, safety, environmental sustainability, and skill development.

RS Metrics Used in this Research for Evaluating Sustainability Performance of Recovery Service Providers or RSPs

The RS metrics are also ratios.

RS1: Quality Compliance is measured as AQP defined as (1- Scrap rate), The lowest AQP is the metric here considering all types of recovered modules. AQP is determined based on Sampling test analysis for a consignment based on agreement between SC and the RSPs.

RS2: It is exactly same as QS 2 applicable for supplier sustainability metric.

RS3: % waste disposal regulation compliance

RS4: Lowest OEE of supplier's production equipment as a % of Target OEE according to contract.

RS5: OSHA performance = 1 - (% non-compliance OSHA requirements for the last quarter).

RS6: Reduction in per product energy consumption and generation of harmful emission as a % of target value for these according to contract, lowest one is the measure for evaluation.

RS7: Employee turnover, 1- (% turnover).

Estimating Re-manufactured and New Product Volume for Economic Sustainability

Let returns to be collected, as a % of demand D_p for a product p, be denoted by $prcD_p$; amount of demand to be met by new product be denoted by nxD_p. Denoting V_p as the price and APC_p as the average cost per product, profit from new product is given by $nxD_p\,(V_p - APC_p)$. If the SC decides entire demand D_p is to be met by new product, overall profit is: $D_p\,(V_p - APC_p)$. An economically sustainable business model with closed loop SC that markets new and re-manufactured product should at least achieve this same profit level. As such, the SC under consideration should earn at least $(1 - nx)\,D_p\,(V_p - APC_p)$ profit from re-manufactured product.

Let rpV_p be the price and $rcAPC_p$ be the average cost per re-manufactured product, where rp and rc are percentages (%) of new product price and cost. To have economic sustainability discussed above: $rpV_p < V_p$ and $rcAPC_p < APC_p$. Let rxD_p be the amount of re-manufactured product to be realized and sold by the SC to earn a targeted profit level to be economically sustainable, where rx denotes the % of product demand D_p.

Evidently $rxD_p \neq (1 - nx)D_p$. Following examples of Xerox and other companies, the quality of remanufactured product is similar to that of new ones, but unit price is lower than that of the new product (i.e. $rpV_p < V_p$). Considering this lower price and the fact that the arc welders, TIG and MIG are not prestige items, it is reasonable to assume that market demand for re-manufactured product will be more than $(1 - nx)D_p$. So, the profit from the re-manufactured product is $rxD_p(rpV_p - rcAPC_p)$. Hence, for the business to be sustainable, we have:

$$rxD_p(rpV_p - rcAPC_p) \geq ((1 - nx)D_p(V_p - APC_p), \text{ or } rx/(1 - nx) \geq (V_p - APC_p)/(rpV_p - rcAPC_p) \quad (29)$$

Based on the market trend, any used product such as engines, forklifts, or welders are sold at 50% to 60% price of new product based on internet search. For an example, in the Amazon on line market they provide 47 % discount on used ESAB EMP 215ic TIG/MIG/ Stick welding 120/230 Volt transformer. By remanufacturing, quality is enhanced and product warranty offered. So for the product (welders) considered in this research, it is reasonable to assume that the price for re-manufactured product, rpV_p, can be 50% to 60% of V_p (new product price). Suppose the SC decided to select $rp = 0.5$ for quick marketing. Let a reasonable estimate for new product price $V_p = 1.15APC_p$ (for 15% gross profit) and, say, the SC decides $nx = 0.5$. Hence, expression (29) may be transformed to: $rx \geq (0.5*0.15)\,APC_p / \{(0.5*1.15 - rc)\,APC_p$, which finally becomes:

$$rx \geq (0.075) / (0.575 - rc) \quad (30)$$

Based on equation (30), the following decision options may be considered for rx: a) if re-manufactured cost/recovered product cost ratio is rc=0.5, $rx \geq 1$. This means that the SC needs to go for realizing and marketing re-manufactured product equal to the current entire demand, which is infeasible, when 50% market for the product is covered by new product. Market size for re-manufactured product cannot grow so much. So, a reasonable plan for recovered product cost rc must be lower than 50% of new product cost APC. Using equation (30), we have the following results:

b) if $rc = 0.45$, $rx \geq 0.6$; c) if rc = 0.42, $rx \geq 0.483$; d) if $rc = 0.4$, rx ≥ 0.428; e) if $rc = 0.35$, $rx \geq 0.33$

Based on the above analysis, say the SC decides to set a target cost for obtaining re-manufactured product cost at or lower than 45% of average new product realization cost including disposal cost. Based on the experience of one of the authors who was involved in managing welding transformer manufacturing business, most of the old components for the end of life transformers including the tank/outer shell has some salvage value. As such very minimum disposal cost is there. Such disposal cost is often compensated by salvage value of reusable, recyclable items. By keeping such a cost target for re-manufactured product, the SC is also assuming that the lower price (50% of V_p) for re-manufactured product will facilitate a market growth of approximately 10% (rx = 60%) based on Pang, et al. (2015). Based on previous experience on recovery by RSPs, out of collected returns approximately 20% of the recovery may not be suitable for making an acceptable quality module for re-manufactured product. As such, the SC should plan to collect customer returns equivalent to $D_p(\,rx = 0.60)/(1\text{-}0.2) = 0.75\,D_p$.

Analysis on Consideration of Demand Growth and Cost Improvement

Table 12 presents model solutions for various scenarios of demand growth and cost improvement potentials on the overall business performance. Since organizations impart high importance to sustainability performance, Solution 5 in **Table 9** with *SUS* value of 0.969 is considered as a base case for this analysis.

Based on the literature, we assumed demand growth potential GR(*i*) as a % of overall demand and cost improvement potential RE(*i*) as a % of overall costs for various functions for the example SC. Referring to the discussion in the Numerical example, the assumed demand growth potential GR(*i*) considered: U (0.05 0.15); and cost improvement potential RE(*j*) for production: U (0.05, 08); RE(s) for supply: U (0.5, 0.10) and RE(*v*) recovery and remanufacturing: U(0.03, 0.07);, following uniform distributions for each potential. SCs may actually obtain improvements out of such potentials for demand growth and cost improvement by closing sustainability gaps (minimizing *SUS* value) through improvement options. Model solutions analyzed here shows the degree to which these potential may be obtained by satisfying user objectives for derived levels of sustainability (*SUS)* performances.

Table 12 shows 12 scenarios out of which, the first four scenarios for model solutions applied *average cost improvements* and *demand growth potentials* (Table 12). Cost improvement potentials remain unchanged for these first four solutions (**Table 11**) but demand growth potential is varied in a decreasing trend in four steps {0.1, 0.08, 0.07, and 0.05}to study their impact on overall SC performances in model solution: maximize *Profit* s.t. $SUS \leq 0.969$. For the solution in Scenario 1, the model solution maintained the *SUS* value by investing $0.368M for the required improvements options. The combined effect of cost improvement for production, supply, and recovery as well as demand growth reduced production, supply, and recovery cost, which together reduced total cost by $0.358M, shown as savings (**Table 12**). For this problem, the model solution could obtain 7.6% (0.076) demand growth out of 10% or 0.1 as potential. A similar result for actual cost reduction, which is lower than the potential for improvement, happened. For example, out of average cost improvement potential {0.065, 0.075, 0.05}, model solution could obtain {0.04; 0.049; 0.037}, as may be seen in the **Table 12**. These are such because the targeted potential may be obtained by making overall gap equal to zero as against model achieved an overall gap $SUS = 0.969$.

In these first four scenarios for model solutions, decrements of demand potential are studied. As demand growth potential decreases from 10% to 5%, the profit, cost, and cost savings also decrease. Profit decreased to $2.769 million from $2.926 million with the decrease in demand growth. Since the model solution had to produce a lower amount of product to satisfy lower customer demand, production, supply and recovery cost went down, resulting in a lower total cost to go down to $8.426 from $8.679 million. Consequently, savings from production, supply and recovery have gone down (see **Table 12**). However, investment to improve sustainability performance by minimizing *SUS* remained the same ($0.368 million) to ensure $SUS \leq 0.969$.

In the next four-solution scenarios (5, 6, 7, and 8) *cost reduction potentials* due to sustainability improvement are ignored to study how overall SC performance is influenced if only demand growth occurs. As expected, these solutions do not have any cost savings but investment amounts are still the same as previous scenarios. This is because the model still needed to ensure $SUS \leq 0.969$ by investing in improvement options. These four solutions have higher costs compared to the previous ones as the consequence of not considering cost reduction options. For example, total cost was $9.038 M in the first solution of these four scenarios (5, 6, 7, and 8), compared to $8.679M for the first solution of previous scenarios (1, 2, 3, and 4). For the solutions (for scenarios 5, 6, 7, and 8) profits decreased to ${2.567; 2.51; 2.481, 2.424} million compared to ${2.926; 2.863; 2.832; 2.769} millions, respectively, of the previous solutions.

Table 12 Study of Solution 5 in Table 9 by varying demand and cost improvement potential

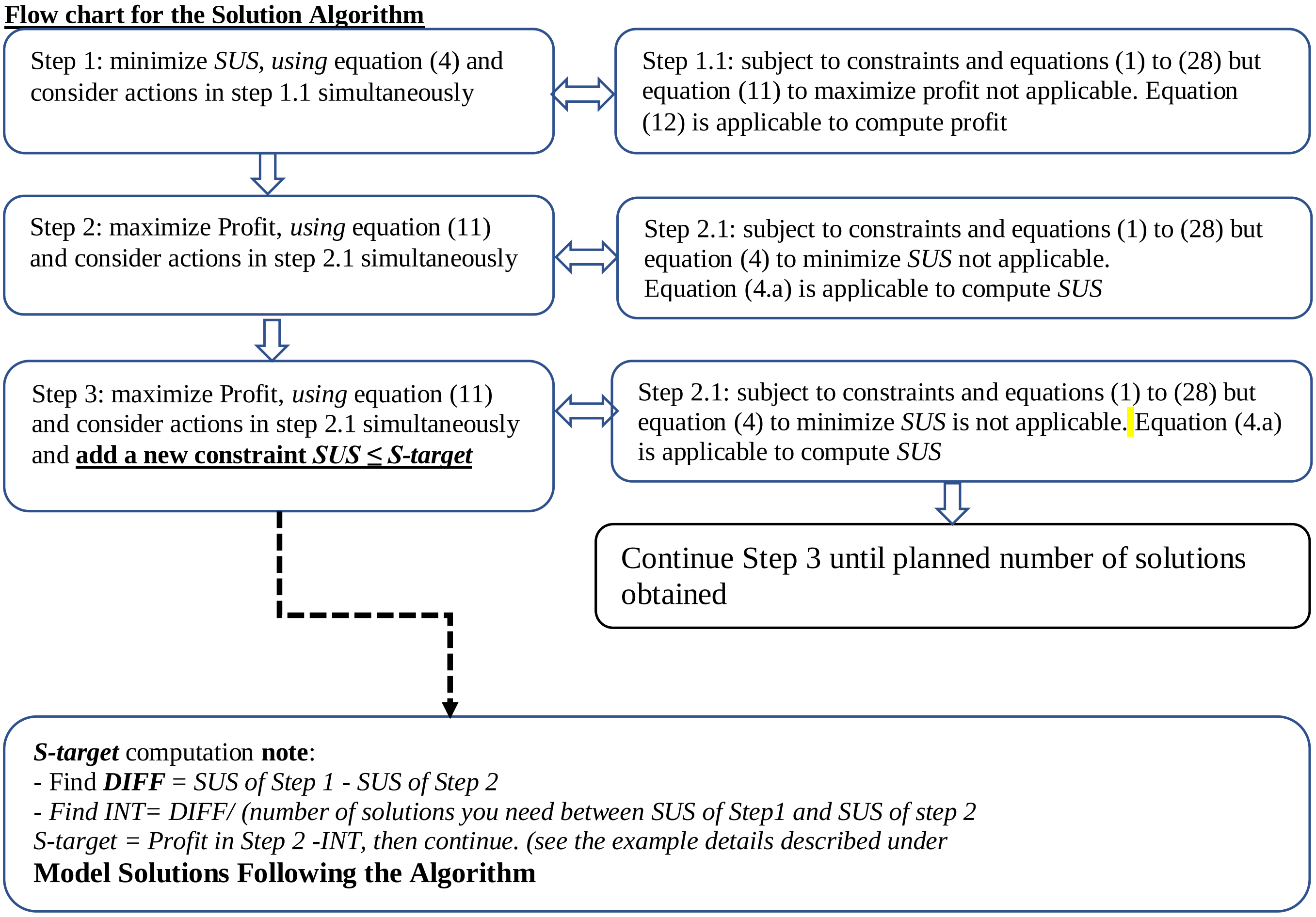
Sc	Average cost improvement (RE(j); RE(s); RE(v)		Demand Growth		*SUS*	Investment M$	Total cost $M	Profit $M	Cost Savings $M
	Potential	Solution	Potential	Solution					
1	0.065;0.075;0.05	0.04;0.049;0.037	0.1	0.076	0.969	0.368	8.679	2.926	0.358
2	0.065;0.075;0.05	0.04;0.049;0.037	0.08	0.061	0.969	0.368	8.578	2.863	0.353
3	0.065;0.075;0.05	0.04;0.049;0.037	0.07	0.053	0.969	0.368	8.527	2.832	0.351
4	0.065;0.075;0.05	0.04;0.049;0.037	0.05	0.038	0.969	0.368	8.426	2.769	0.346
5	0	0	0.1	0.076	0.969	0.368	9.038	2.567	0
6	0	0	0.08	0.061	0.969	0.368	8.931	2.51	0
7	0	0	0.07	0.053	0.969	0.368	8.878	2.481	0
8	0	0	0.05	0.038	0.969	0.368	8.772	2.424	0
9	0.065;0.075;0.05	0.04;0.049;0.037	0	0	0.969	0.368	8.174	2.613	0.333
10	0.052;0.06;0.04	0.037;0.0390.029	0	0	0.969	0.368	8.241	2.547	0.2666
11	0.032;0.038;0.025	0.023;0.025;0.018	0	0	0.969	0.368	8.34	2.446	0.166
12	0	0	0	0	0.969	0.368	8.507	2.28	0

In the last four scenarios (9, 10, 11, and 12), the influence of demand growth potential is ignored (made 0); and cost improvement potentials are gradually decreased. For example, solutions in scenario 10 considered 80% of cost improvement in scenario 9; scenario 11 considered 50% of cost improvement in scenario 9; and solution in scenario 12 considered no cost improvement option. Out of these last four scenarios, total cost for last solution (scenario 12) is the highest out of these four scenarios (9, 10, 11, 12), and profit is the lowest out of all the 12 scenarios. Cost is not the highest of all the scenarios because quantity produced is lower than the solutions for scenarios 1 to 8.

As discussed previously, the solution in scenario 12 is not practical. Prior literature provides much evidence that sustainability improvement steps to eliminate waste, reduce energy and harmful emissions, improve costs, and eliminate obsolescence, all of which, in turn reduce costs and create competitive pricing for demand growth (Kleindorfer et al., 2005). So, it is almost certain that by addressing sustainability steps to ensure $SUS \leq 0.969$, will definitely benefit the organization to obtain a cost reduction and demand growth up to an extent.

Solutions in **Table 12** provide the following managerial insights: 1) The research assumed demand growth potential through improving sustainability performance. Based on evidence in the literature (EPA, 2000, EPA 2016), such potential is applicable in any business. These solutions show that by closing sustainability performance gap (minimizing *SUS*) with benchmarked target performances, the business can achieve demand growth nearer to growth potential or a target they can earn; 2) the investment made by an organization to improve sustainability performance also provides them cost savings as shown in **Table 12**. SC managers may refer to improvement criteria followed by world class organizations, like, GM, Toyota, 3M, Lockheed Martin and organize sustainability based training for their employees such that the entire organization may appreciate how sustainable practices can create growth potential for the firm and improve economic as well as social performance of the firm. 3) Although, the solution in scenario 12 is not practical based on examples of several companies that are following sustainable practices, it shows the minimum cost implication \$0.368M (just 4% of original cost) that an organization needs to commit to obtain impressive sustainability performance ($SUS \leq 0.969$) without taking into consideration the growth potential and cost reduction potentials. Such sustainability performance will support them to comply with regulatory requirements, improve market image and in turn obtain overall SC performance improvement subsequently.4) The analysis in **Table 12** will provide clearer insights to SC managers to *select trade off solution* based on **Table 8** and 10.

Flow chart for the Solution Algorithm



Options for improvement of Sustainability Performances considered in the Research

Options considered for improving supplier's performance include supporting:

1. In new technology to reduce energy consumption and harmful emission, quality improvement
2. In information technology to increase visibility, implement JIT and eliminate inventory, obsolescence, reduce price, increase responsiveness
3. By training on lean, quality management, modifying production system to enhance quality

4. Supplying metallic packing containers to eliminate use of packaging for modules to improve environment conformance
5. Providing training on resiliency practices in machine reliability, safety, product design, and other economic performance, including emergency handling and planning
6. Providing support to select new materials, new methods for productivity and environmental performance

Options to improve Production Plant Sustainability performances

1 Investment in new technology
2 New product design with new materials
3 Training and development
4 Utilizing flexible plants
5 Installing Audit team, ISO 14000 and other measures
6 More control on RSP, Supplier and collaboration with Customer and Advertising

Options to improve Sustainability performances of RSPs

1. By providing training on lean, quality management, modifying recovery steps to enhance quality
2. By including investment in using fixtures, and other tools for refurbishing
3. Providing training and support to maintain database and using information system to improve visibility with customers
4. Training on complying OSHA, EPA, City, and statement waste, and emission related requirements
5. New investment in assembling modules to improve productivity
6. Investing in manipulator, materials handling equipment for materials transportation, dismantling, and finally quality enhancing steps.

For the SC operated plant fixed cost for investment is considered for the sustainability performance improvement options, assuming SC's own operations will be able to adapt to such investments and implement them based on Direct SC management control.

Table 13: Typical improvement through the sustainability improvement options

	Performance metric for production plant		
Plant	**(PS1)**	**PS2**	**PS3**
Improvement Effect of improvement **option 1** for plants (current PS values)			
1	0.019(0.95)	0.025(0.96)	0.008(0.98)
Improved PS Values if **option 1** is applied by the model			
1	0.95 +0.019 =0.969	0.96+.025 = 0.985	0.98+0.008 =0.988
	Performance Metric for Supplier		
Supplier	**QS1**	**QS2**	**QS3**
Improvement Effect of improvement **option 5** for suppliers (current QS values)			
1	0.01(0.99)	0.009(0.99)	0.029(0.98)
Improved QS values if **option 5** is applied by the model			
1	0.999	0.999	*Model will not select this option
	Performance Metric for RSP		
RSP	**RS1**	**RS2**	**RS4**
Improvement effect Improvement **option 2**(current RS value)			
1	0.96(0.011)	0.97(0.023)	0.94(0.008)
Improved RS values if **option 2** is applied by the model			
1	0.96+0.011=0.971	0.993	0.948

Although similar investment may be applicable for improving sustainably performance of suppliers and RSPs, SC will be interested in implementation oriented project to have the impact on their supplies from the investment. Only investment in the improvement project may not be meaningful when they do not have direct control on Suppliers and RSPs.

As is apparent, each improvement options for plants, or applicable option for suppliers, or RSPs, may be made applicable for each of the sustainability improvement metrics relevant to plants, suppliers or RSPs. Only difference may be some options will provide comparatively higher impact and some lower. We assumed effect of the options varies randomly following U (0.005 to 0.035).

We present typical effects of improvement options in **Table 13**. The Model constraint (10) included such improvements for improving performance. We illustrated improve effect for typical cases in **Table 9**. For an example, current values of plant 1 performance metrics PS1, PS2, PS3 are 0.95,0.96, 0.98, respectively for these three performance metrics. If the model applies Improvement option 1 for plant 1, PS1 will be improved by 0.019 making it 0.95+0.019=0.969; PS2 by 0.025 making it 0.968; and PS3 by 0.008 making it 0.988, as may be observed in **Table 13**. The improvement cases of suppliers and RSPs as presented **Table 13** may be similarly explained.

Dr. Kanchan Das is an Associate Professor in the Technology Systems Department of East Carolina University, North Carolina, USA. He received his PhD in Industrial Engineering from the University of Windsor, Ontario, Canada. His research interests include mathematical modeling of design and planning of sustainable and Resilient supply chain management. He also conducts research on humanitarian logistics planning. His current research foci include integration of Lean systems, sustainability considerations, risk management, and resiliency planning in supply chain design and management. He is a member of Decision Sciences Institute and Institute of Industrial and Systems Engineers.

Dr. Amit Mitra is a Professor in the Department of Systems and Technology in the Herbert College of Business at Auburn University, Auburn, Alabama, USA. He received his PhD in Management Science from Clemson University, Clemson, South Carolina, USA. He has published numerous journal articles and is the author of the book, “Fundamentals of Quality Control and Improvement”, Fourth Edition, Wiley, 2016. His research interests are in the statistical process control, applied statistics, healthcare and service quality. He is a member of the Institute for Operations Research and Management Sciences, Decision Sciences Institute, and the American Statistical Association.