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A novel two-stage mathematical model for green supplier development

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Abstract

Nowadays, numerous processes of any supply chain are done by suppliers and consequently they cause a massive amount of pollution released to the nature. Hence, greening the suppliers has become a necessity. Although most of green supplier development programs need high investment, formal optimization models that address this issue are very rare. This paper mainly aims to address this problem by introducing a two-stage mathematical model which can help managers allocate optimal investment in their suppliers. In the first stage, suitable green supplier development programs are selected. Then, a multi-objective optimization model is presented for investing in an appropriate set of green programs, concurrently. Moreover, the conceptual framework presented in this paper provides managerial insight in every step of this process. Also, a comprehensive analysis is done under two scenarios of budget estimation and it has been found that these programs highly influence their required investment, and therefore, they must be considered, simultaneously.

Keywords: Green supply chain management; green supplier development programs; non-linear multi-objective optimization model.

1- Introduction

Environmentally-friendly programs have received an enormous attention during the past decades and companies have been trying to improve their supply chain environmental performance (Chiou and Chan, 2011). Suppliers are considered as one of the most important members in supply chains. In order to create a green supply chain, it is necessary to improve both suppliers and producers' environmental performance. Many suppliers are not able to focus on their environmental problems due to their limited budget; therefore, they need help from the manufacturer (Talluri et al., 2010, Mani et al. 2015). Green supplier development is one of the best methods in which the buying firm aims to help suppliers improve their

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environmental performance (Hickle, 2013). However, green supplier development is a relatively new approach and mathematical decision models in this area are limited (Bai and Sarkis, 2010).

Implementing a supplier development process, especially the green one, needs managerial support as well as accurate budget allocation due to the limited budget of companies (Talluri et al., 2010). Thus, it is crucial for managers to access to decision models in every step of this process. It is noteworthy that there is no concise definition for a green supplier in the literature. Firms consider specific suppliers as green ones based on regulations as well as their own needs and expectations. Nevertheless, environmental criteria used for green supplier selection and evaluation include pollution control, existence of environmental management systems, fusil fuel, renewable energy consumption and eco-design (Kannan et al., 2015). These criteria and also firms' expectations can be inferred as a base to define green supplier development programs that refers to programs which help suppliers improve their environmental performance (Bai and Sarkis, 2010). Obviously, there is a wide range of environmentally-friendly programs each of which tends to improve particular aspects of suppliers' environmental performance. Investing in all green supplier development programs (GSDPs) is practically impossible due to companies' various environmental needs and their limited budget. The aforementioned facts imply that selecting an appropriate set of GSDPs is a key factor towards implementing a successful green supplier development process. It is important to point out that selected supplier development programs must align with the buying firm's strategies (Krause and Ellram, 1997) to satisfy its goals and create a win-win situation which applies in the content of GSDPs as well. To this end, investment decisions must be made considering advantages and disadvantages of GSDPs simultaneously.

Many researchers have addressed programs and practices to reduce environmental burden. For example, closed-loop strategies like repair, reuse, refurbishment, remanufacturing, recycling were considered (Ettehadieh, 2011; Saavedra and Barquet, 2013; Kerr and Ryan, 2001; Hatcher et al., 2011). The role of advanced technologies (Hammar and Lofgren, 2010; Frondel et al., 2007) to reduce waste, pollution and consumption of natural resources and energies is also another core area of study in the literature (Makarieva et al., 2008; Ackermann et al., 1999; Sims et al., 2003; Gerlagh and Zwaan, 2006). Other types of studies mainly include classification of GSDPs and development of decision models for selecting GSDPs (Bai and Sarkis, 2010; Dou and Zhu, 2013; Fu et al., 2012). Also, a wide range of studies have investigated green supplier selection and evaluation (Ho et al., 2010; Kannan et al., 2015). Moreover, investment in the content of supplier development process and the importance of this matter has been studied (Talluri et al., 2010).

However, to the best of our knowledge, there are a limited number of studies that addressed green supplier development programs in terms of mathematical modeling. In other words, the existing studies have made managerial implications and explored various attainable benefits of GSDPs, and the optimal investment allocation is unexplored yet. Besides, companies tend to consider a wide range of environmental and operational criteria while improving their supply chain performance. Therefore, not only investment issues must be considered towards a practical implementation of GSDPs, but also different needs of both suppliers and manufacturer as well as the suitable set of GSDPs to overcome their environmental needs must be considered, simultaneously. Also, this paper highlights the importance of budget allocation in the context of green supplier development process.

The remainder of this paper is organized as follows: The next section reviews literature in the area of green supplier development. Section 3 presents conceptual framework of the model. In section 4, GSDPs are selected using Analytic Hierarchy Process (AHP) and a novel multi-objective model for optimal investment in GSDPs is presented. In sections5 and 6, we provide results and discuss the obtained results, respectively. Then, in the last section, conclusion and opportunities for future studies are presented.

2- Literature Review

Conceptual models presented in the literature have studied strategic process of supplier development (Kraue and Ellram, 1997; Krause and Handfield, 1998).Yet, decision models for green supplier development are rare (Bai and Sarkis, 2010; Dou and Zhu, 2013; Fu et al., 2012). Akman (2014) evaluated suppliers in an automobile manufacturing company via green criteria to include GSDPs. First, suppliers were selected via operational criteria including delivery, cost, service and quality and next they were clustered with fuzzy C-means method. Akman then clustered the best cluster of suppliers in three main categories: good, medium and poor performers and suppliers in poor environmental condition were evaluated. Several studies have explored various environmentally-friendly programs which can help companies reduce their environmental burden (Dou and Zhu, 2013; Fu et al., 2012). However, it is necessary to select a proper set of GSDPs to reach companies' green goals. Dou and Zhu (2013) proposed a model to evaluate green supplier development programs with respect to supplier involvement propensity.

Table1. Types of GSDPs and their advantages

Type of GSDP	Description	Advantage	Reference
Green technology	Clean technology**:** reduces pollution production and/or waste production End-of-pipe solution (EOP):prevents pollution release to the environment (e.g. coolers and filters)	Pollution reduction Waste reduction Reduction in use of natural resources	Hammar and Lofgren(2010) Frondel et al. (2007)
End-of-life strategies	Recycling Remanufacturing Re-use Servicing Disposal	Cost reduction of disposal Preservation of natural resources Pollution reduction Energy saving	Jofre and Morioka (2005) Kim et al. (2006) Kerr and Ryan (2011) Sutherland et al. (2008) Ameli et al. (2016)
Renewable energies	Solar Wind Biomass Hydro-electric	Reduction of greenhouse gas emissions Reduction in use of natural resources	Sims et al. (2003)
Green raw material	Non-toxic and renewable raw material which can be either partially or totally green	Preservation of natural resources Reduction in ecosystem damages Reduction in emissions through disposal processes	Noci (1997)
Green R&D	Reducing environmental burden by changing product design and material	Reduction of end-of-life damages Reduction of Production processes	Cao and Yao (2013)

They considered pollution control, pollution prevention, environmental management system, and resource consumption and pollution production as supplier environmental performance factors. They have found that supplier involvement propensity must be considered to implement successful supplier development programs. Fu et al. (2012) introduced a managerial approach to evaluate green supplier development programs at a telecommunication systems provider. The focus of their study was on interrelationship between GSDPs and their importance for the company. This model can be used to help managers prioritize GSDPs. Sarkis et al. (2010) categorized green supplier development programs in three main groups: 1-green knowledge transfer and communication, 2- investment and resource transfer, and 3- management and organizational practices. They have used rough set theory on a data sample and studied how green development programs influence business performance as well as environmental performance. In real situation, many practices are placed in these three groups. However, it is not reasonable for an enterprise to invest in all programs that may adopt. According to the company's goals, policies and expectation, suppliers' needs as well as available budget, proper programs must be selected. Several environmentally-friendly programs have been developed to protect the environment through the past decades; such as utilizing green technology, i.e. clean technology and end-of-pipe solutions (Hammar and Lofgren, 201; Frondel et al., 2007); using renewable energies (Makarieva et al., 2008; Ackermann et al., 1999; Sims et al., 2003; Gerlagh and Zwaan, 2006), end-of-life strategies, e.g. remanufacturing, recycling, refurbishment and reuse (Jofre and Morioka, 2005; Ettehadieh, 2011; Saavedra and Barquet, 2013; Kerr and Ryan, 2001; Hatcher et al., 2011), green R&D (Cao and Yao, 2013) and using green raw material (Noci, 1997; Awasthi et al., 2010).

Table 2. Review of the most related studies

Writer	Subject	Green Supplier Development	Supplier Development	Mathematical Model for Investment	Environmental Criteria	Operational Criteria
Dou and Zhu (2013)	Evaluating green supplier development programs with a grey-analytical network process-based methodology	✓	-	-	✓	✓
Fu et al., (2012)	Evaluating green supplier development programs at a telecommunications systems provider	✓	-	-	✓	✓
Bai and Sarkis, (2010)	Green supplier development: analytical evaluation using rough set theory	✓	-	-	✓	✓
Talluri et al., (2010)	Manufacturer cooperation in supplier development under risk	-	✓	✓	-	✓
Kannan et al., (2015)	Multi-criteria decision making approaches for green supplier evaluation and selection: a literature review	-	-	-	✓	✓
Akman, (2014)	Evaluating suppliers to include green supplier development programs via fuzzy C-means and VIKOR methods	✓	-	-	✓	✓
The proposed model	A novel two-stage mathematical model for green supplier development	✓	-	✓	✓	✓

Aforementioned programs are briefly described in table 1. Companies need to prioritize their environmental needs and goals to invest optimally in appropriate GSDPs. Besides, all the environmentally-friendly programs are not suitable for green supplier development process because of the nature of the problem. However, all environmentally-friendly programs are not totally green; they have specific advantages and disadvantages (Ettehadieh, 2011). Given various kinds of GSDPs and companies' environmental criteria as well as business criteria, it is crucial for managers to make an informed decision to obtain desired results. The way that GSDPs may apply improvements to green goals is also described in this section. Several green development programs have been proposed in the literature (Bai and Sarkis, 2010; Frondel et al., 2007; Jofre and Morioka, 2005; Makarieva et al., 2008; Cao and Yao, 2013).

In this paper, nine programs have been identified as proper GSDPs through a comprehensive review of the literature and in-depth interview with the managers of a leading Iranian automotive company, which are briefly outlined in table 1.A concise review of the most related studies and their main features are illustrated in table 2.

3- Conceptual Framework

Schematic presentation of green supplier development process is shown in figure 1. As can be seen, the strategic process of green supplier development commences with the support of top-level managers. In the next step, suppliers are selected according to environmental and operational criteria. In real situations, it is more likely that both categories of criteria are considered. The main reason to implement green supplier development process for a company is to reach its desired environmental goals. Hence, comparing the current and desired environmental performance of suppliers is essential. By that means, the capacity, environmental requirements and opportunities for suppliers to implement GSDPs are determined. As previously mentioned, each GSDP may apply certain improvements. Hence, to enhance particular green goals, supplier’s needs and characteristics of GSDPs must be measured simultaneously; and as a result, a proper set of GSDPs are selected. AHP is used in this study for selection of GSDPs. More details are given in subsection 4.1. In the most important level of this process, the optimal monetary amount is allocated in each GSDP in each supplier via the mathematical model. After budget allocation, GSDPs are implemented and in the last level, environmental performance of suppliers must be evaluated to measure the effectiveness of the GSDPs as well as to specify suppliers’ future needs.

3-1- Methodology and Model

In this section, first proper GSDPs are selected by means of AHP. The criteria used and the results are given in subsection 4.1. Afterwards, a novel mathematical model is presented for investment in the selected GSDPs according to six environmental objective functions. Mechanism of the model and objective functions are described in subsection 4.2.

3-1-1- Selection of GSDPs

There are several environmental criteria to be optimized in selection of GSDPs and obviously it is impractical to focus on all of them. First, an appropriate set of green criteria is specified to select GSDPs. Next, proper GSDPs are selected regarding to their impact on the green criteria. This is considered as a multi-criteria decision making (MCDM) problem due to the different criteria that are selected by companies. MCDM approaches are widely studied in the literature. Ho et al., (2010) examined MCDM approaches used in supply chain management between 2000 and 2008. Their research was focused on selection and evaluation of suppliers in order to reduce the number of them to cooperate with reliable ones. According to their results, AHP and its combination with other approaches is one the most popular and common approaches among MCDM methods in supply chain management.

As mentioned above, many environmental criteria have been studied in selection and evaluation of green suppliers (Noci, 1997; Kannan et al., 2015; Dou and Zhu, 2013). In this study, after a comprehensive interview with managers of the automotive company about their priorities, budget, green policies and the most environmental problems of their key suppliers, four green criteria are selected as pollution reduction, waste reduction, life-cycle cost reduction and reduction in consumption of natural resources.

As stated before, AHP is adopted to select proper GSDPs in this paper. The first stage of this approach is to design hierarchical structure of the decision problem which is divided into three levels. At the first level, the objective of the decision making problem is specified. At the second level, evaluation criteria are located and finally, alternatives are placed in the last level. AHP approach works based on pair-wise comparisons which aid to show relative importance of each criterion. Next, relative importance of the alternatives is calculated with respect to the criteria.

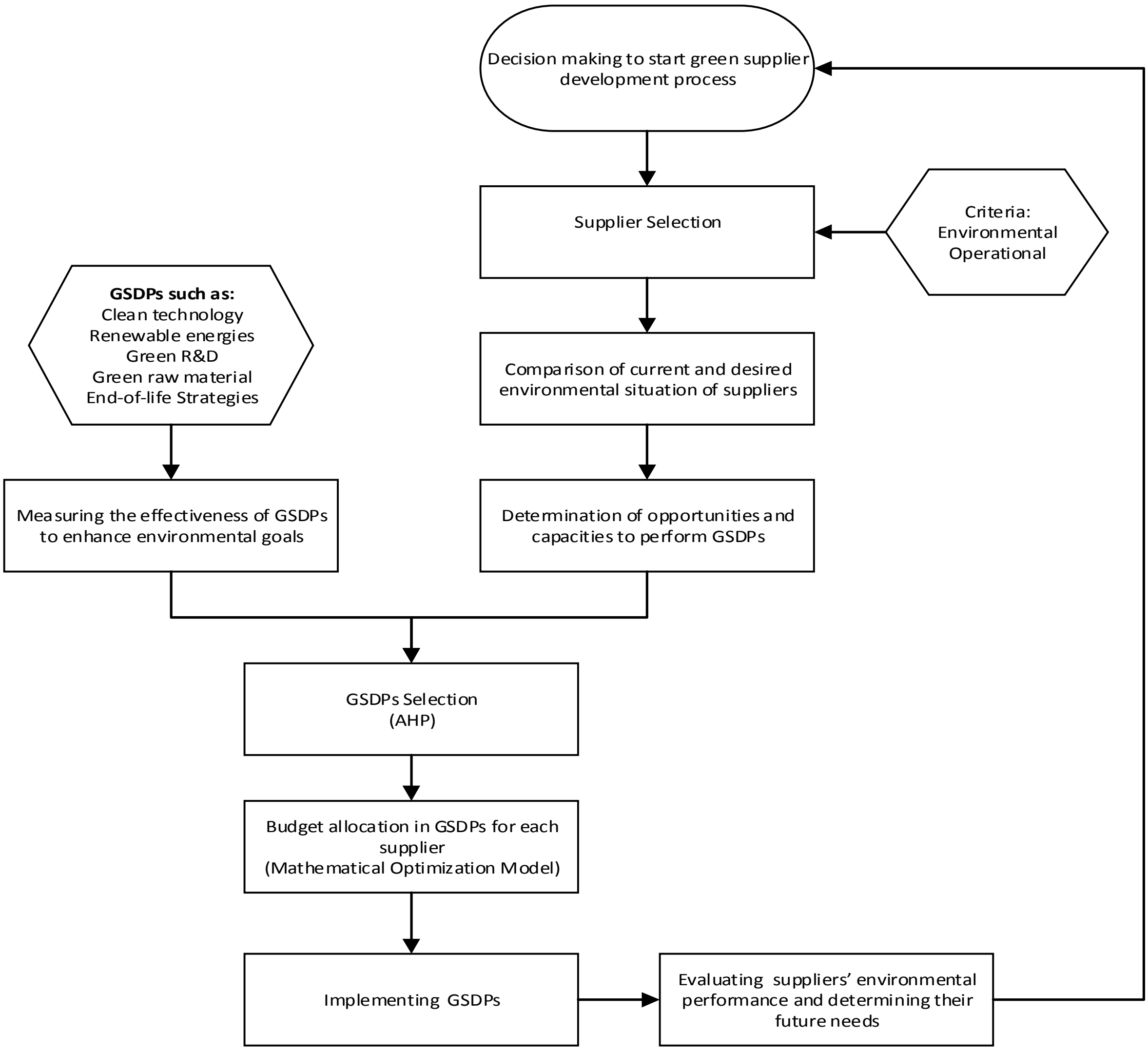

Figure 1. Conceptual framework for green supplier development

Consequently, alternatives are prioritized based on their gained weight. For more details please read (Saaty, 1980).

Table 3. Relative importance of green criteria

Green Criteria	Weight
Pollution reduction	0.626
Life-cycle cost reduction	0.2482
Reduction in consumption of natural resources	0.0884
Waste reduction	0.0366

A questionnaire was designed based on AHP approach for the stated criteria and GSDPs and was sent to the managers of the automotive company. The results of pair-wise comparisons of chosen environmental criteria are summarized in table 3with respect to notions of managers.

Table 4. Comparison of GSDPs

GSDPs	Preference degree
Clean technology	0.3692
Remanufacturing	0.1392
Renewable energy	0.1341
Green raw material	0.1295
Green R&D	0.1127
Recycling	0.0837
Refurbishment	0.0157
Reuse	0.0155

Next, GSDPs are ranked with respect to weights of the criteria. Results gained from the comparison of GSDPs are shown in table 4.According to the results given in table 4 and after an interview with the managers regarding to their budget limits, desired conditions to implement GSDPs and considering possible disadvantages of GSDPs versus their benefits, clean technology, remanufacturing, renewable energy, green raw material and green R&D are selected.

3-1-2- Mathematical Model

The proposed model aims to optimize monetary investment in the GSDPs for key suppliers. The model inputs include suppliers' environmental requirements as well as GSDPs' specifications. In this model, optimal investment is calculated according to the way that GSDPs help suppliers satisfy their environmental objectives as well as their existing capacity of implemented GSDPs. As mentioned above, all the green objectives cannot be satisfied giving a limited budget and due to suppliers' different capabilities, it is necessary to select and prioritize green goals. Implementing GSDPs may accomplish various environmental goals. Therefore, the monetary amount that manufacturer invests in a GSDP depends on the amount invested in other GSDPs as well as the priority of environmental goals.

Table 5. Notations for the mathematical model

Indices	Description
W	Green supplier development program index: *r*: Remanufacturing *RE*: Using renewable energy resources *GRD*: Green R&D *CT*: Utilizing clean technology *GM*: Using green raw material
I	Supplier index
J	Product index
L	Raw material index
k	Part index

(Continued)

Parameters	
n	The number of suppliers
m	The number of products
K	The number of parts
GD_{ij}^{max}	The maximum achievable green degree of product *j* supplied by supplier *i*
X_{ij}^{ret}	The annual returned product *j* supplied by supplier *i*
D_j^{Total}	The annual demand of product *j*
MU_{jl}	The amount of raw material *l* used in unit product *j*
$DPart_{jk}$	The number of part *k* used in unit product *j*
C_l^M	The cost of unit raw material *l*
C_l^{GM}	The cost of unit green raw material *l*
C_{ij}^{rd}	The unit cost of green R&D effort to increase unit green degree of product *j* supplied by supplier *i*
q_{ik}	The rate of reusable part *k* disassembled by supplier *i*
CBC_{ij}^{da}	The unit cost of disassembling product *j* supplied by supplier *i*
CBC_{ik}^{ref}	The unit cost of refurbishing disassembled part *k* by supplier *i*
CBC_i^{RE}	The unit cost of consuming energy from renewable resources
$CBC_{\mathrm{ij}}^{\mathrm{CT}}$	The cost of utilizing clean technology to supply unit product *j* by supplier *i*
CGD_{ij}	The green degree of product *j* supplied by supplier *i*
$Ca_{ij}^{n,NT}$	The non-clean production capacity of supplier *i* for manufacturing product *j*
CCa_{ij}^{da}	The capacity of supplier *i* for disassembly of product *j*
CCa_{ik}^{ref}	The capacity of supplier *i* for refurbishing of part *k*
CCa_i^{RE}	The capacity of supplier *i* for using energy supplied from renewable resources
CCa_{ij}^{CT}	The capacity of supplier *i* in manufacturing product *j* with clean technology
$CGMU_{ij}$	The amount of green raw material *l* used in unit product *j* by supplier *i*
$EC_{ij}^{n,CT}$	The energy consumption of unit product *j* manufactured by supplier *i* with clean technology
$EC_{ij}^{n,NT}$	The energy consumption of product *j* manufactured by supplier *i* with non-clean technology
$EC_{\mathrm{ij}}^{\mathrm{r}}$	The energy consumption of unit product *j* remanufactured by supplier *i*
EM_i^{coal}	The amount of CO2 emission resulting per kWh of electricity generated by fossil fuel resources used by supplier *i*
EM_i^{RE}	The amount of CO2 emission resulting per kWh of electricity generated by renewable energy resources used by supplier *i*
Wst_{ij}^{CT}	The amount of waste generated in while manufacturing unit product *j* using clean technology by supplier *i*
Wst_{ij}^{NT}	The amount of waste generated in while manufacturing unit product *j* using non-clean technology by supplier *i*

$CoRed_j^{GRD}$	The amount of reduction in environmental costs (dollars) by increasing unit green degree to product *j*
$CoRed_l^{GM}$	The amount of reduction in environmental costs (dollars) by using unit green raw material *l*
$CoRed_j^{disp}$	The amount of reduction in environmental costs (dollars) by preventing from disposal of unit product *j*
$C_l^{env,M}$	The environmental cost of using unit raw material *l*
$C_j^{env,RD}$	The environmental cost of non-environmentally friendly design of product *j*
$C_j^{env,disp}$	The environmental cost of disposal of unit product *j*
Decision variables	Description
$X_{ij}^{n}\begin{cases}X_{ij}^{n,CT}\\X_{ij}^{n,NT}\end{cases}$	The number of product *j* supplied by supplier *i* $\begin{cases}utilizing\ clean\ technology\\utilizing\ non-clean\ technology\end{cases}$
X_{ij}^{r}	The number of product *j* remanufactured by supplier *i*
X_{ij}^{da}	The number of product j disassembled by supplier *i*
$EC_{ij}^{n,CT,Coal}$	The amount of energy consumption of manufacturing unit product *j* with fossil fuel resources
$EC_{ij}^{n,NT,Coal}$	The amount of energy consumption to manufacture unit product *j* utilizing non-clean technology and using fossil fuel resources by supplier *i*
$EC_{ij}^{r,Coal}$	The amount of energy consumption to remanufacture unit product *j* using fossil fuel resources by supplier *i*
$EC_{ij}^{n,CT,RE}$	The amount of energy consumption to manufacture unit product j utilizing clean technology and using renewable energy resources by supplier *i*
$EC_{ij}^{n,NT,RE}$	The amount of energy consumption to manufacture unit product j utilizing non-clean technology and using renewable energy resources by supplier *i*
$EC_{ij}^{r,RE}$	The amount of energy consumption to remanufacture unit product j using renewable energy resources by supplier *i*
GD_{ij}	The green degree of product *j* supplied by supplier *i*
GMU_{ijl}	The amount of green raw material *l* used in unit product *j* supplied by supplier *i*
Ca_i^{RE}	The annual capacity of supplier *i* in using electricity generated by renewable resources
$Inv_{i\,w}$	The amount manufacturer invests in supplier *i* on GSDP *w*

Notations for the proposed model are summarized in table 5.Implementation of GSDPs may need different requirements. For the sake of simplicity, the following assumptions are considered:

1- Every raw material has a green alternative.

2- Using green raw material or increasing green degree of a product/part does not affect required technologies and/or processes.

3- All parts of a remanufactured product consist of reusable disassembled parts.

4- Every green R&D effort increases unit green degree of the product at the current development period.

5- Every environmental capability of each supplier is utilized.

6- Annual demand is satisfied by new as well as remanufactured products (i.e. there is no difference between new and remanufactured products to customers).

Formulation of model is given next. First, we provide the objective functions.

$$f_1 = min \sum_{i=1}^{n} \sum_{j=1}^{m} (EC_{ij}^{n,CT,Coal} X_{ij}^{n,CT} + EC_{ij}^{n,NT,Coal} X_{ij}^{n,NT} + EC_{ij}^{r,Coal} X_{ij}^{r}) \quad (1)$$

$$f_2 = min \sum_{i=1}^{n} \sum_{j=1}^{m} \left(EM_i^{coal} EC_{ij}^{n,CT,coal} + EM_i^{RE} EC_{ij}^{n,CT,RE}\right) X_{ij}^{n,CT} + \left(EM_i^{coal} EC_{ij}^{n,NT,coal} + EM_i^{RE} EC_{ij}^{n,NT,RE}\right) X_{ij}^{n,NT} + \left(EM_i^{coal} EC_{ij}^{r,coal} + EM_i^{RE} EC_{ij}^{r,RE}\right) X_{ij}^{r} \quad (2)$$

$$f_3 = min \sum_{i=1}^{n} \sum_{j=1}^{m} (C_j^{env,RD} - CoRed_j^{GRD} GD_{ij}) \quad (3)$$

$$f_4 = min \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{l=1}^{L} MU_{jl} \, (C_l^{env,M} - CoRed_l^{GM} GMU_{ijl}) \quad (4)$$

$$f_5 = min \sum_{i=1}^{n} \sum_{j=1}^{m} C_j^{env,disp} X_{ij}^{ret} - CoRed_j^{env,disp} X_{ij}^{r} \quad (5)$$

$$f_6 = min \sum_{i=1}^{n} \sum_{j=1}^{m} Wst_{ij}^{CT} X_{ij}^{n,CT} + Wst_{ij}^{NT} X_{ij}^{n,NT} \quad (6)$$

The objective functions are subject to the following constrains.

$$\sum_{w} \sum_{i=1}^{n} Inv_{iw} \leq B \,, \forall i \quad (7)$$

$$Inv_{i\,r} = \sum_{j=1}^{m} (X_{ij}^{da} - CCa_{ij}^{da}) CBC_{ij}^{da} + \sum_{j=1}^{m} \sum_{k=1}^{K} (X_{ij}^{r} DPart_{jk} - CCa_{ik}^{ref}) \, CBC_{ik}^{ref} \,, \forall i \quad (8)$$

$$Inv_{i\,RE} = (Ca_i^{RE} - CCa_i^{RE}) CBC_i^{RE}, \forall i \quad (9)$$

$$Inv_{i\,GRD} = \sum_{j=1}^{m} C_{ij}^{rd} \left(GD_{ij} - CGD_{ij}\right), \forall i \quad (10)$$

$$Inv_{i\,GM} = \sum_{j=1}^{m} \sum_{l=1}^{L} (\left(C_l^{GM} - C_l^{M}\right) GMU_{ijl}), \forall i \quad (11)$$

$$Inv_{i\,CT} = \sum_{j=1}^{m} (X_{ij}^{n,CT} - CCa_{ij}^{n,CT}) CBC_{ij}^{n,CT}, \forall i \quad (12)$$

$$GMU_{ijl} \leq MU_{jl} \,, \forall i,j,l \quad (13)$$

$$X_{ij}^{da} \leq X_{ij}^{ret}, \forall i \quad (14)$$

$$\sum_{k=}^{K} X_{ij}^{r} \, Dpart_{jk} \leq \sum_{k=1}^{K} q_{ik} X_{ij}^{da} \, Dpart_{jk}, \forall i,j \quad (15)$$

$$X_{ij}^{n,NT} \leq Ca_{ij}^{n,NT}, \forall i,j \quad (16)$$

$$\sum_{i=1}^{n} X_{ij}^{r} + X_{ij}^{n} = D_j^{Total}, \forall j \quad (17)$$

$$Ca_i^{RE} = \sum_{j=1}^{m} (EC_{ij}^{n,CT,RE} X_{ij}^{n,CT} + EC_{ij}^{n,NT,RE} X_{ij}^{n,NT} + EC_{ij}^{r,RE} X_{ij}^{r} \,, \forall i) \quad (18)$$

$$EC_{ij}^{n,CT,RE} + EC_{ij}^{n,CT,coal} = EC_{ij}^{n,CT}, \forall i,j \quad (19)$$

$$EC_{ij}^{n,NT,RE} + EC_{ij}^{n,NT,coal} = EC_{ij}^{n,NT}, \forall i,j \quad (20)$$

$$EC_{ij}^{r,RE} + EC_{ij}^{r,coal} = EC_{ij}^{r}, \forall i,j \quad (21)$$

$$X_{ij}^{n} = X_{ij}^{n,CT} + X_{ij}^{n,CT}, \forall i,j \quad (22)$$

$$GD_{ij} \leq GD_{ij}^{max}, \forall i,j \quad (23)$$

$$X_{ij}^{da}, X_{ij}^{r}, X_{ij}^{n}, X_{ij}^{n,CT}, X_{ij}^{n,NT}, EC_{ij}^{n,RE}, EC_{ij}^{r,RE}, EC_{ij}^{n,coal}, EC_{ij}^{r,coal}, GMU_{ijl}, GD_{ij}, Inv_{iw}, Ca_{i}^{RE} \geq 0, \forall i,j,l,w \quad (24)$$

Objective functions are described as follows. Objective function (1) is to minimize the use of fossil fuels which results in pollution prevention as well as reduction in the use of natural resources. Objective function (2) is defined to minimize environmental pollution. Objective function (3) aims to minimize the environmental burden of non-green products. Objective function (4) minimizes environmental burden caused by using non-green raw material. Objective function (5) tries to minimize end-of-life damages of the products. Objective function (6) is to minimize waste which is important due to energy saving, pollution prevention, preservation of natural resources, etc.

There are complicated constraints when investing in different GSDPs, concurrently. Some of them are program specific and the other ones are pertaining to interrelationship between the GSDPs which are described below. Expression (7) is the budget constraint. Expressions (8)-(12) are the investment constraints for remanufacturing, using renewable energy resources, using green raw material and utilizing clean technology, respectively. Expression (13) requires that the green raw material used in unit product cannot exceed the total required raw material in unit product. Expression (14) shows that the amount of disassembled product cannot exceed the amount of returned product. Expression (15) ensures that the number of parts used in remanufactured products cannot exceed the number of reusable disassembled parts. Expression (16) guarantees that the quantity of product j produced by non-clean technologies cannot exceed its capacity. Expression (17) represents that the annual demand is satisfied by both new and remanufactured products. Expression (18) calculates the annual amount of renewable energy consumption of suppliers. Expressions (19)-(21) compute energy consumption of new product utilizing clean technology, non-clean technology and remanufactured product, respectively. Expression (22) shows that new products may be produced with clean and/or non-clean technology. Expression (23) restricts the maximum achievable green degree of products. Expression (24) guarantees non-negativity of decision variables.

4- Results

Providing experimental results, we will show how the proposed model works. It is important to estimate the model parameters properly to reach reliable results. Required monetary investment in GSDPs is directly related to in what manner they aid in improving environmental goals. A small set of parameters related to the characteristics of suppliers are real data given from the automotive company. Other parameters are tuned to keep their logical interrelationship according to the literature. For example, a research on remanufacturing in Xerox Company has shown that remanufactured products with eco-design can reduce energy consumption up to 68%and consequently, pollution production would be decreased(Kerr and Ryan, 2011).We assume that energy can be saved and waste can be reduced by utilizing clean technology. It is obvious that the reduction amount in energy consumption, waste production and pollution production is related to many factors such as product type and technology used, etc. Many researchers have studied renewable energy resources and their environmental advantages. For example, it has been found that providing 1KW/h energy by burning coal produces almost 0.25 Kg of

CO_2 which can be avoided by using renewable energies such as solar energy (Sims et al., 2003). Above mentioned facts has been considered to estimate model parameters. We assume that there are four types of products and four key suppliers each of which supplies one type of product.

Table 6. The annual demand of products

Product type	1	2	3	4
Annual demand	10000	5000	10000	80000

Table 7. The amount of used and returned products

Product type	1	2	3	4
Returned product	2000	2000	35000	2500

Table 8. The number of part requirements in unit product

Part type Product type	1	2	3	4	5
1	2	0	1	0	0
2	5	0	0	0	0
3	0	0	0	1	0
4	0	1	3	0	1

Table 9. The rate of waste according to technology type

Supplier Waste (%)	1	2	3	4
Waste (non-clean tech)	0.15	0.18	0.2	0.15
Waste (clean tech)	0.1	0.1	0.15	0.09

Table 10. The amount of required raw material (50 grams) in unit product

Raw material type Product type	1	2	3	4	5
1	4	4	0	4	4
2	5	5	0	5	5
3	20	0	0	20	0
4	8	3	6	8	3

Table 11. The amount of energy consumption according to technology type and remanufacturing

Product Energy consumption (KW/h)	1	2	3	4
Manufacturing unit product by existing technology	7	8	10	15
Manufacturing unit product by clean technology	5.5	7.5	8.5	4
Remanufacturing	4.2	6	8	3.5

Table 12. Green R&D data

Supplier Cost ($)	1	2	3	4
R&D effort level	500	550	600	700
Environmental cost of non-green product	20	35	30	40
Cost reduction caused by increasing unit green degree to product	0.2	0.35	0.3	0.4

Table 13. Environmental costs associated with product end-of-life phase

Product Cost ($)	1	2	3	4
Environmental cost of product end-of-life phase	1	1.5	1	2
The amount of reduction in environmental costs (dollar) by remanufacturing unit product	0.7	0.95	0.75	1.2

Table 14. Costs associated with raw material.

Raw material Cost ($)	1	2	3
Unit non-green raw material	2	1.5	2.5
Unit green raw material	3	2	3.5
Environmental cost of unit non-green raw material	5	10	3
The amount of reduction in environmental costs (dollar) by using unit green raw material l	3.5	10	2

The suppliers' data are shown in tables 6-14. Table 6 shows the annual demand of products. Table 7 presents the amount of used products that are collected and returned to the manufacturer at the current development period. Table 8 shows bill of material for the products. Table 9 indicates waste rate of products according to the technology type which is either clean technology or non-clean technology. Table 10 specifies the amount of required raw material (50 grams) in unit product. Table 11 illustrates the amount of energy consumption according to technology type and whether it is manufactured or remanufactured. Table 12 presents data related to green R&D program. For the sake of simplicity, it is assumed that the maximum achievable level of greenness for all products is 100%; that means it is possible to reach a completely green product by performing required green R&D efforts. Table 13 depicts environmental costs associated with product end-of-life phase i.e., costs related to the environmental damages occur because of leaving used products in the nature, and also the amount of possible cost reduction by implementing end-of-life strategies, as mentioned in section 4, remanufacturing is selected among the end-of-life strategies in this case. Table 14 illustrates costs associated with types of raw material (green or non-green) as well as environmental costs for using different types of raw material. It is a hard task to estimate the cost of environmental burdens occurred due to product design and used raw material precisely. In order to describe the role of GSDPs in the model it is assumed that there is a possibility to compensate environmental damages completely by implementing the GSDPs. For example, using unit green raw material type 1 can reduce environmental cost of using non-green raw material to 3.5 dollars. If the environmental cost of using green raw material type 1 is assumed to be 5 dollars, this kind of raw material is not totally environmentally-friendly. Raw material type 2 is assumed to be green completely. Every possible condition is considered in this case with above mentioned assumptions. Note that there is no existing capacity of suppliers for implementing any kind of GSDPs.

The proposed model is a multi-objective mixed-integer non-linear programming that is a complex model to solve. As a limited number of suppliers and GSDPs are used as inputs of the model, the number of decision variables reduces and the model could be solved by exact method using GAMS software. This model is solved via goal programming technique which is a powerful and effective methodology for the modeling and solving the multi-objective problems (Ignizio and Romero, 2003).

According tothe objectives of the Iranian automotive company, the goals are set to be 20% improvement from the existing environmental situation of the suppliers, e.g. 20% improvement from existing amount of pollution production for each supplier. Another important factor to be set is total required budget for supplier development programs. It is necessary to estimate company's budget properly to implement development plans, successfully. In this research in order to provide better insight, the model is solved and sensitivity analyses are done under two scenarios of budget estimation: underestimated budget and overestimated budget. In real situations, companies do not always afford green investments according to the standards, regulations and their environmental need. Moreover, it is not clear how much benefit they can achieve from investing in different green programs, concurrently; thus, in many cases budget is under-estimated. Let’s assume that 500000 dollars is required to reach the mentioned goals; underestimated budget is set to be 350000 dollars and overestimated budget is set to be 750000 dollars.

Table 15. Monetary amount ($) invested in GSDPs for overestimated budget

GSDP Supplier	R	GM	RE	CT	GRD	Total
1	7485.714	17240.81	29857.14	85714.28	10000	150297.95
2	8526.31	9984.96	31611.84	16578.94	11000	77702.06
3	12413.33	18133.33	58666.66	85333.33	14000	188546.66
4	11250	6306.66	24166.66	38333.33	12000	92056.66

Table 16. Monetary amount ($) invested in GSDPs for underestimated budget

GSDP Supplier	R	GM	RE	CT	GRD	Total
1	7485.71	0	57649.29	11601.88	10000	86736.89
2	8526.31	0	31611.84	16578.95	11000	67717.11
3	12413.33	0	84288.26	17009.08	14000	127710.7
4	11250	0	30138.22	14447.11	12000	67835.33

The model is solved and results are presented in tables 15-16.As can be seen, optimal investments in GSDPs change enormously with respect to budget estimation. When the budget is over-estimated there is no barrier to reach the green goals; therefore, the required budget is allocated in the GSDPs. However, when the budget is underestimated the impact of GSDPs on improvement of the green goals is a key issue in budget allocation. As mentioned before, some GSDPs influence objectives simultaneously, e.g. remanufacturing reduces energy consumption, pollution production, and raw material usage and end-of-life environmental burdens. It is obvious that such programs can help reach the goals as much as possible when the budget is not enough to obtain all the green objectives. Thus, the model allocates more money in these programs compared to the others.

5- Discussion

Strategic process of supplier development is directly related to suppliers' existing capacity to perform green development programs. It is obvious that if a supplier has proper condition to implement certain GSDPs needs less investment in that area to achieve certain goals. This situation is addressed by sensitivity analyses on suppliers' existing green capacities. Note that the suppliers' green capacities include existing capacity of suppliers to do the selected GSDPs. Sensitivity analyses done based on existing green capacities of suppliers include five major parts as follows: suppliers' existing capacity of 1-disassembly site which represents capacity of remanufacturing in this study, 2-using renewable energies, 3-utilizing clean technologies, 4-using green raw material and 5- existing green degree of the products which denotes supplier's green R&D capabilities. The number of used and returned products to the suppliers is another key factor to analyze the proposed model. These products are referred as goods supplied in the past which has reached their end-of-life phase in the current development period. Investment in end-of-life strategies, as previously mentioned remanufacturing is chosen among end of life strategies in this case, is dependent on the above mentioned products. In this section, green capacities of one of the suppliers, supplier 1, are analyzed in order to show how existing capacities of suppliers effect optimized investments in other GSDPs as well as total investment in suppliers for over-estimated and under-estimated budget. For the sake of simplicity and to prevent repeating the gained results, we will show results of analyses on capacity for one of the GSDPs namely remanufacturing. According to the definition of remanufacturing (Kim et al., 2006), it starts with collecting used products from customers. Other stages include disassembly, refurbishment and assembly. In remanufacturing process, all parts of a used product are disassembled. Reusable parts are cleaned, refurbished and repaired if necessary. Next, they are assembled to remanufacture a product. Required parts of a remanufactured product may be given from usable disassembled parts or/and new parts. Non-reusable parts are considered as waste. Thus, existing capacity of suppliers for remanufacturing consists of two main parts: the first part includes capacity of disassembly site and the second part includes capacity of refurbishment and assembly sites which are dependent to the first part. If a supplier remanufactures products, first, disassembles returned products then investigates parts and selects renewable ones, then finally refurbishes and re-assembles reusable parts. For the sake of simplicity, sensitivity analyses on remanufacturing capacities of suppliers are done only based on the capacity of disassembly site. Based on the suppliers' data presented in section 5, no supplier is able to remanufacture its products in development period. Maximum number of used and returned products to supplier1 is set to be 2000 units. The following diagrams show how capacity of disassembly for a supplier changes optimized investment in other GSDPs under over-estimated and under-estimated budgets. As can be seen in figure 2, when the capacity of remanufacturing facilities for supplier 1 increases, the required investment in remanufacturing facilities decreases; which happens to achieve certain green goals. The monetary amount needed for the GSDPs on other suppliers remain constant due to over-estimated budget. That means with the over-estimated budget all green goals are achievable. According to figures 2-6, this matter is true for all the GSDPs of supplier1. Figure 3indicates that varying the capacity of remanufacturing facilities for supplier1 from 1 to 1500 units of products does not affect the amount invested in clean technology facilities of this supplier.

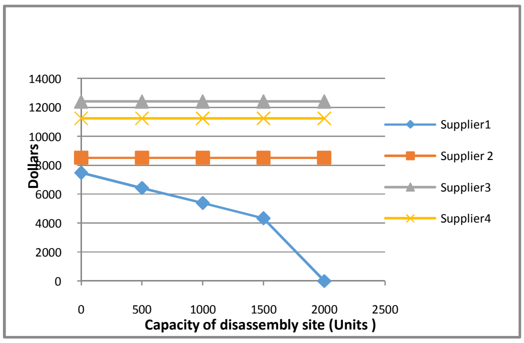

Figure 2. Investment in remanufacturing (over-estimated budget)

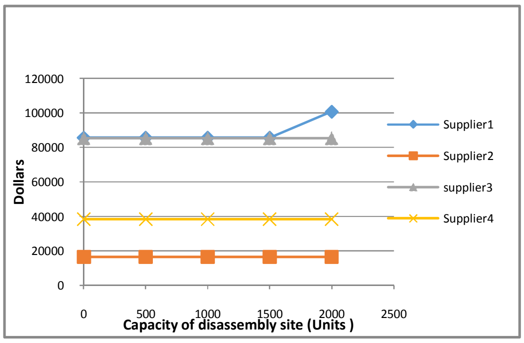

Figure 3. Investment in clean technology (over-estimated budget)

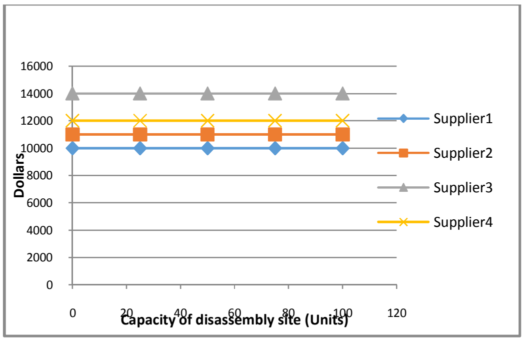

Figure 4. Investment in green R&D (over-estimated budget)

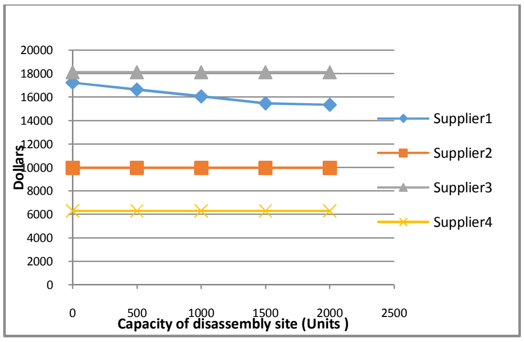

Figure 5. Investment in green raw material (over-estimated budget)

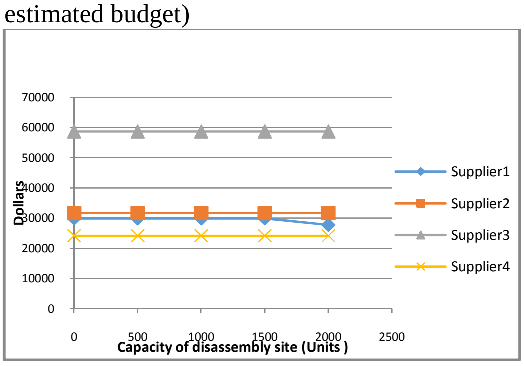

Figure 6. Investment in renewable energy (over-estimated budget)

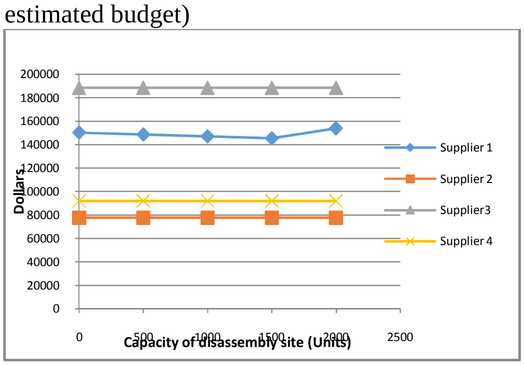

Figure 7. Total investment in suppliers (over-estimated budget)

According to figure 5, as the capacity of remanufacturing facilities of supplier1 upturns, optimal investment in green raw material for this supplier declines. Because more remanufactured products lead to less manufactured or new products to meet the annual demand which indicates less raw material is used. Therefore, environmental burden related to the use of non-green raw material decreases. Results illustrated in figure 6shows that a change in the capacity of remanufacturing facilities for supplier 1, from 1 to 1500 units of products does not vary required investment in renewable energies since supplier1 can increase the number of remanufactured products in this range. There is a reduction in monetary invested in renewable energies for supplier1, from 1500 to 2000 units of products. As can be seen in figures 1-6 investment in clean technology and remanufacturing rises, and as a result, consumption of fossil fuels as well as pollution production reduces in this domain.

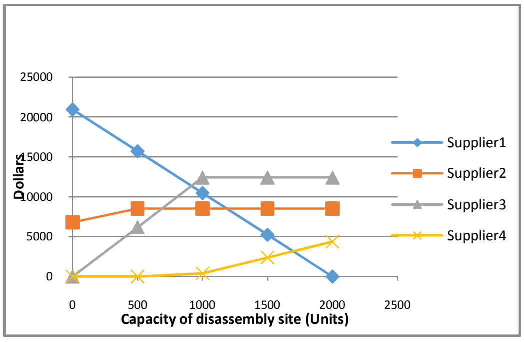

Figure 8. Investment in remanufacturing (under-estimated budget)

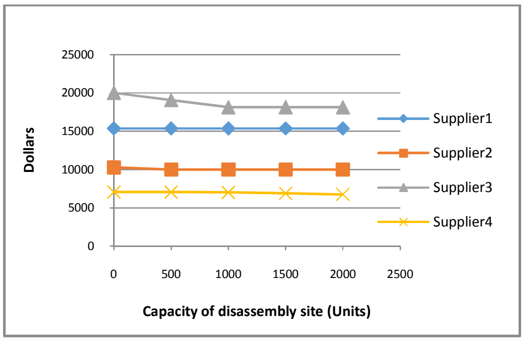

Figure 9. Investment in green raw material (under-estimated budget)

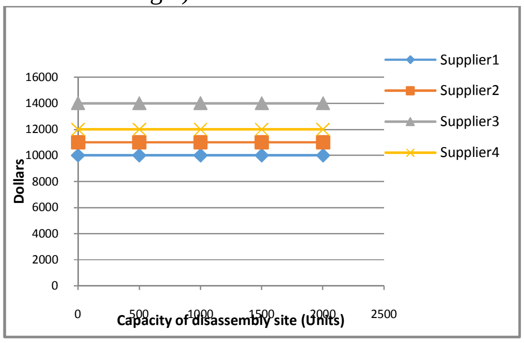

Figure 10. Investment in green R&D (under-estimated budget)

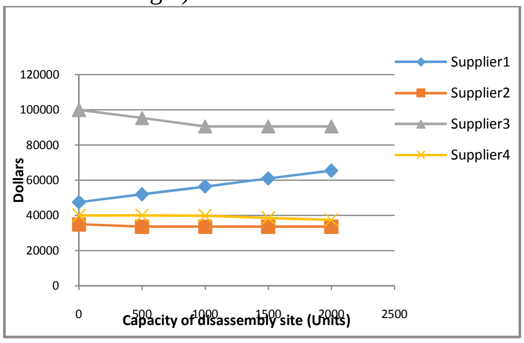

Figure 11. Investment in renewable energy (under-estimated budget)

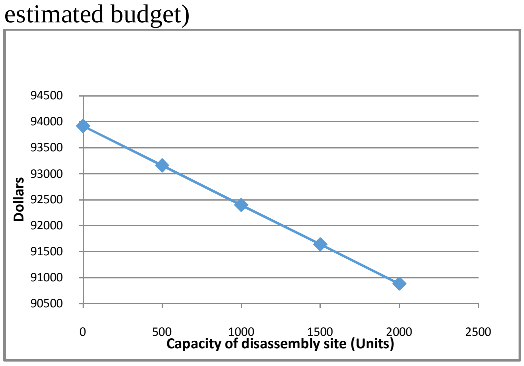

Figure 12. Investment in supplier1 (unde-estimated Budget)

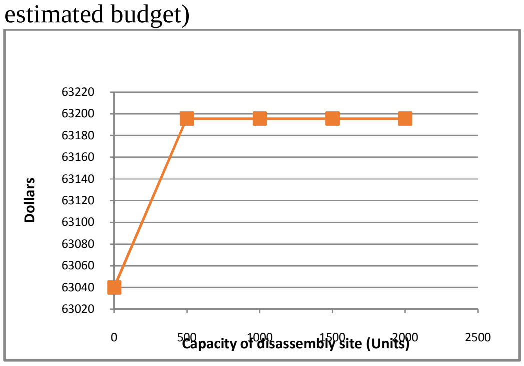

Figure 13. Investment in supplier2 (unde-estimated budget)

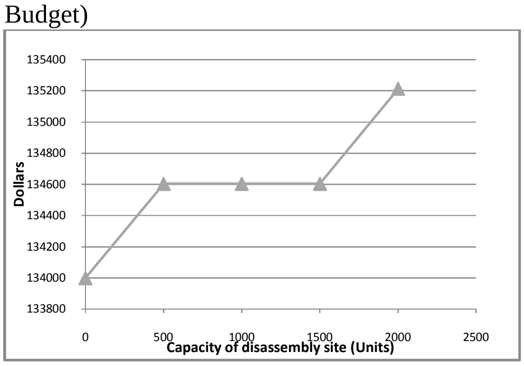

Figure 14. Investment in supplier3 (under-estimated budget)

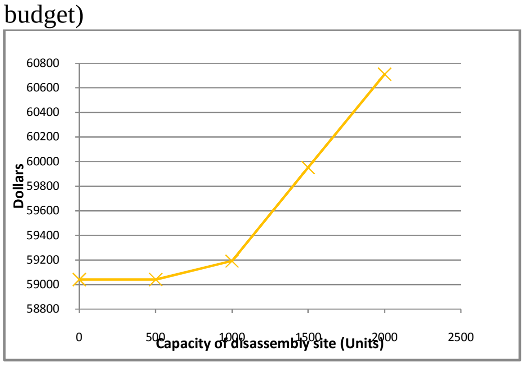

Figure 15. Investment in supplier4 (under-estimated budget)

Thus, there is less need for investment in renewable energies. Total investment, i.e. the sum of investment in all GSDPs, in suppliers is presented in figure 7. As can be seen in figures 2-7, a change in investment in a particular GSDP varies the amount invested in the other GSDPs because of their advantages and disadvantages against each other.

As mentioned before, the whole set of green goals cannot be fulfilled when the budget is underestimated. Thus, there exist deviations from determined goals. In given situation, the better environmental performance of suppliers, i.e. more existing capacity of GSDPs, the less need for investment in related GSDPs. In order to reduce deviations from goals, the remaining budget is invested in the GSDPs that make maximum improvement in environmental performance of suppliers according to their ability to enhance goals as much as possible. Thus, a change in a suppliers' existing capacity of GSDPs varies total required investment in the other suppliers.

Results illustrated in figure 8 indicate that when supplier 1 does not remanufacture products, there is not enough budgets to invest in other suppliers. As the existing capacity of manufacturing of supplier 1 increase, the released budget is assigned to other suppliers to reduce deviation from goals. Figures 9-11show that as supplier 1 remanufactures more products, the required investment in green raw material as well as utilizing renewable energies by supplier 1 reduces; because, the consumption of natural resources as well as pollution production which are considered as the main purposes of using renewable energies is reduced by remanufacturing. Also, the number of new products diminishes by remanufacturing, and subsequently, the usage of raw material declines. As illustrated in figures 12-15, when the capacity of remanufacturing for supplier 1 increases, total investments in other suppliers rise to minimize deviation of goals. Since given budget is enough to fulfill green goals of supplier 1, the required investment in this supplier decreases by increasing its remanufacturing capacity.

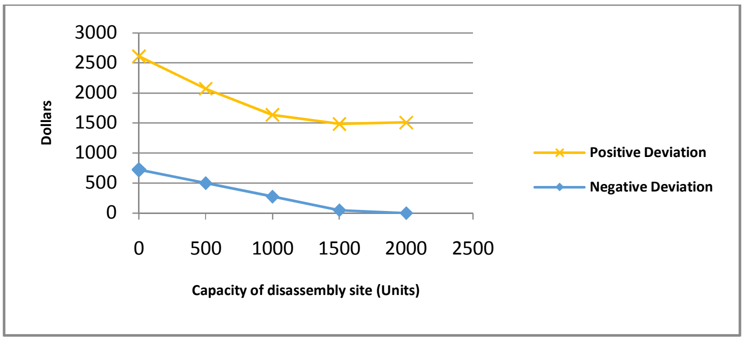

Figure 16. Deviation from goals (under-estimated budget)

The more suppliers perform GSPDs, the better environmental performance they have. Figure 16 shows that in given situation with an under-estimated budget, it is possible to decline the positive deviations by investing in other suppliers. Negative deviation which indicates improvement superior to 20% environmental improvement of suppliers also reduces by enhancing existing capacity of supplier 1.

6- Conclusion

Significant role of suppliers in supply chain processes and the fact that an enormous amount of environmental burden is caused by poor environmental performance of suppliers have made companies to develop their suppliers, environmentally. Suppliers usually need help from manufacturer because either they don't have enough budget or are not inclined to invest in this field because of the high resource-consuming nature of GSDPs. Limited budget of companies is a major barrier for green supplier development due to this fact that almost all GSDPs need high monetary investment. This paper mainly discussed the investment aspect of green supplier development process. In this research, first, a conceptual framework for practical implementation of GSDPs was proposed which provides managers with insight to the whole process of green supplier development that focuses on investment on GSDPs. This model was run on data given from a leading Iranian automotive company. Then, the green goals of the buying firm were compared to environmental requirements of their selected suppliers; and a set of useful GSDPs was determined. The main contribution of this study was a multi-objective optimization model for investment in GSDPs. In this model, four key suppliers and five GSDPs including remanufacturing, clean technology, renewable energies, green raw material and green R&D were considered, concurrently. The proposed model showed how the way that GSDPs affect green goals varies their required investment. Then experimental results were performed to analyze and validate the model. The sensitivity analysis emphasized that GSDPs affect each other and must be considered simultaneously to achieve certain goals.

With respect to the growth of environmental regulations and concerns world-wide, investigating financial advantages of green supplier development can be an interesting future research topic. Additionally, in real situations, many companies share suppliers. Developing the model in the case of multiple-manufacturer multiple-supplier will help manufacturers to identify the benefits of cooperation in green supplier development.

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