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# Multi-objective mathematical modeling for sustainable supply chain management in the paper industry

**Abstract**

This work develops a multi-objective linear programming model for a multi-echelon, multi-product, multi-period supply chain planning. This model considers all dimensions of sustainable development paradigm simultaneously and expands six objective functions for making the model realistic. To solve this model and large-scale sustainable supply chain management, an improved version of the augmented ε-constraint method (AUGMECON2) is used. Computational results illustrate the proposed model admitted various progresses in all the three pillars of sustainable development; namely remarkable progress, mildly progress and irregular one, respectively. In addition, important managerial insights are provided. Trade-off interactions between multi-objectives are perceived by the obtained Pareto solutions that represents the cost of being sustainable from the point of optimizing the social factors and environmental impacts. An application to the paper industry is presented and discussed.

*Keywords:* Supply chain management; Multi-objective programming model; Chemical process; Sustainability; ε-constraint method.

## 1. Introduction

The main objective of a supply chain master planning (SCMP) problem is to determine purchase, production and distribution quantities for facilities in a supply chain. Whereas for many years, minimizing the total cost or maximizing the revenue was the major aim of supply chains, responsibility for the environmental and social impacts of SC processes and products, the safety and health of their employees and the entire community are still lacking attention. Moreover, some governments have enacted legislations in favor of the environment, such as regulations for greenhouse gases (GHGs) reduction in European Union, Australia and Canada (Devika et al. 2014).

Sustainable SCM (SSCM) is defined as considering the environmental and social impacts of SC operations as well as its economic performance in management of information, material and capital flow (Seuring and Müller 2008). A multi-objective optimization problem (MOP) includes optimizing objective function in a situation that there are more than one objective function while typically conflicting objective functions. MOPs arise in a variety of real word applications and the need for efficient and reliable methods is increasing (Mavrotas 2009). There are differences between single objective and multi-objective optimization, the most difference is that for multi-objective optimization, no single optimal solution exists; however, a set of equally good alternative solutions exist with various trade-offs, known as Pareto-optimal solutions. These solutions are feasible solutions that cannot be enhanced in just one objective function without worsening their performance in at least one of the rest. In the absence of any other information, none of these solutions can be said to be better than the other. The decision maker is usually needed to provide additional preference information and identify the most preferred solution (Mavrotas et al. 2013).

There is an actual necessity to develop a more appropriate and detailed comprehending of sustainability pointedly in relation to supply chains while there is an obviously scientific identification of the need to unify economic, environmental and social sustainability, given the extensive essence of these fields (Ashby et al. 2012). For considering all the economic, environmental and social dimensions simultaneously and in an integrated way, mathematical models enable the effective application of sustainable development principles to SC components (Boukherroub et al. 2014).

According to the current considerations, this paper firstly addresses the issue of multi-echelon, multi-commodity, multi-period SCMP including suppliers, plant and warehouses. Secondly, dimensions of SSCM combine the economic objective of the model with environmental and social impacts that has been extracted from the gaps among the previous studies. Finally, an augmented ε-constraint (AUGMECON2) method is applied to a multi-objective linear programming (MOLP) model that optimizes supply chain operations, environmental and social impacts. The model including six objective functions is solved by the Augmecon method, which finds a set of solutions (i.e., Pareto solutions) authorizing the decision maker to opt the one following the best her/his priorities with respect to environmental, economic and social performances.

This paper is organized as follows. The related previous studies are reviewed in Section 2. In Section 3, an integrated mathematical model is presented leading to the application of the proposed paradigm. Section 4 introduces a case study. Section 5 presents our solution methodology, and Section 6 represents initial results and experiments. Finally, we present the main conclusion and future research in Section 7.

## 2. Literature review

Considering the works addressing multi-objective models in this section, sustainability is the most common issue for adding to the basic economic models (Brandenburg et al. 2014). A few papers, add non-economic objectives (i.e., minimizing transportation time or lead time) or SC risks (e.g., financial risks). In the context of the sustainable supply chain, environmental impacts have been addressed in several papers and in different fields, such as the food industry (Validi et al. 2014a, Validi et al. 2014b and Soyal et al. 2014). However, social impacts have rarely used instead. In evaluating environmental impacts, GHG emissions have been considered in the most studies and then the life cycle assessment (LCA) metric, such as Chaabane at al. (2012).

Luthra et al. (2014) provided an outline of the several subjects related to Green Supply Chain Management (GSCM). They pointed out six key themes of GSCM in their study, but not mentioned the operations research (OR) models. Awudu and Zhang (2012) mentioned different issues for modeling uncertainties and sustainable concepts in biofuel SCM. They discussed the evolution of biofuels, the three types of decision-making levels and uncertainties and how to model uncertainties with sustainable concepts simultaneously. However, they did not address the optimization models.

To model environmental decision making in the reviewed papers, there are four main ways, namely LCA, GHG emissions, quantity of waste generated, and energy consumption. The LCA is a metric for evaluating environmental impacts in all of the components of a supply chain from raw materials to a final product. Executing a methodology (e.g., LCA) is not possible ever for a lot of reasons. Environmental concerns notify in companies slowly, therefore evaluating just a subdivision of environmental factors may be considered as a middle stage on the way complete integration. When gaining environmental data and modeling the entire supply chain is too though, environmental factors could be evaluated partially (Luthra et al. 2014). The other three metrics are suitable for considering the partial assessment of environmental impacts. Table 1 shows the assessing metrics for environmental impacts found in the reference papers.

{Please insert Table 1 about here.}

But, the social metrics of sustainability has been considered rarely in the reviewed papers as a part of mathematical models. Boukherroub et al. (2014) considered “local development” as the main social impact in their mathematical model, whereas the concept of “Work Conditions” has been used by Saffari et al. (2015), You et al. (2012) and Yue et al. (2014).

Boukherroub et al. (2014) proposed an integrated approach for applying sustainable development axioms to supply chain planning models. They used GHG emissions as environmental metrics, local employment and employment stability as social metrics. They used a weighted goal programming method to solve their mathematical model and finally mentioned involving OR decision-making tools for the future studies.

Devika et al. (2014) considered the three aspects of sustainability in the network design problem and developed a mixed-integer programming (MIP) model for the problem. They assumed environmental impacts, environmental benefits of using EOL products and harm caused by products as environmental metrics, fixed and variable job opportunities and work's damage as social metrics. However, they do not address a real case study as a field for application.

A tactical supply chain planning model presented by Fahimnia et al. (2015). This model is suitable for inquiring trade-offs between costs and environmental diminishing made up with energy consumption, carbon emissions and waste generation. The proposed model also combines other features of supply chains in real world, such as lot sizing, multiple transportations and flexible holding volume of warehouses. They supposed the following environmental metrics:

- Carbon pollution in manufacturing, inventory holding and transportation.
- Consumed energy and generated wastes in manufacturing and inventory holding in warehouses and plants.

Their suggestions include modeling the problem at the operational level and the investigation of the affection of organizational decisions on sustainability of communities and industries. Sazvar et al. (2014) developed a stochastic mathematical model and proposed a new replenishment policy in a centralized supply chain for deteriorating items. The optimal solutions, in terms of types of transportation vehicles to be used, are determined as a tradeoff between environmental impact and financial costs/benefits.

Jindal and Sangwan (2016) designed a multi-objective closed-loop supply chain taking the environmental and economic factors in to account with uncertainty in the parameters. They considered carbon footprints of transportation as the environmental metric and solved the model by an interactive epsilon constraint method. A multi-objective model was presented by Entezaminia et al. (2016), in which they consider as well a closed loop green system to be planned on the basis of a multi-site and multi-product supply chain.

Mousazadeh et al. (2014) investigated the design and plan of problems in green and reverse logistics in a fuzzy environment. They considered the total CO2 equivalent emissions as the environmental metric. However, they did not consider social aspects in the sustainability concept and did not combine operational and tactical planning subjects into the present strategic models. Palak et al. (2014) analyzed the affections of carbon regulatory mechanisms on replenishment decisions and utilized mathematical models. For determining emissions as a function of load weight, distance traveled and transportation mode applied, they used relevant methods.

For designing a sustainable medical supply chain network in an uncertainty environment, Pishvaee et al. (2014) proposed a multi-objective possibilistic programming model and considered damage to workers' health, consumer risk, created job opportunities and local development as social metrics and life cycle assessment-based methods as environmental metric. However, they did not consider operational and tactical supply chain decisions under a full sustainability approach. Moreover, they did not include the development of social impact assessment methods.

Taking into account forward and reverse flows altogether via supply chain, Saffari et al. (2015) promoted a supply chain network design model. They used three distinct objectives: total cost, social impacts like recruitment and justice in creating job opportunities and environmental impacts like CO2 emissions. The model looks for optimizing the facility location problem and to determine type of technology, network flows, and volume of manufacturers. Not only the work did not consider multi-period or multi-product related issues in the problem, but there was only one type of transportation mode tackled. They pointed out the need to consider other environmental and social factors such as energy consumption level, local suppliers' priority, industrial centers adjacency, and facilities' distance related to providing new job opportunities. Yu and Solvang (2016a and 2016b) addressed the design of a reverse supply chain with a multi-objective modelling approach in the bio-chemical industry. The latter was interesting for some researchers due to the high environmental impact that could lead to efficient trade-off between the decision criteria of the three pillars of sustainability (economic, environmental and societal).

You et al. (2012) developed an MOMILP model including all aspects of sustainability. The environmental objective is calculated by the life cycle GHG emissions, economic objective is calculated by the total cost, and the social objective is calculated by the number of increased local jobs. However, the work lacked considering efficient optimization algorithms for analysis of nationwide and considering the time-dependent volume expansion plans.

For designing and operating sustainable bioelectricity supply chain networks, Yue et al. (2014) presented a multi-objective optimization model, which considers all three dimensions namely environmental, economic and social factors simultaneously. They considered GHG footprint as an environmental metric and the local job opportunities as a social metric.

As the main conclusion in the context of a sustainable supply chain, it has been deducted that environmental impacts have been mentioned a lot in the published papers; however, social impacts rarely used instead. To discuss about the model types of papers, MOMILP is more used. A few papers have incorporated fuzziness or uncertainties in terms of a specific characteristic of the model types. There are several methods to solve multi-objective models. Such as weighted sum of objectives, epsilon constraint, metaheuristics, goal programming, multi-criteria decision analysis, fuzzy approaches and hybrid methods. For NP-hard conditions, a variety of methods have been created or modified, especially for metaheuristics. The categories of application of the papers and type of their experiments: biomass (biofuel), chemical processes, industrial goods, consumer goods and public sector. Briefly, the contributions of this paper are as follows:

- Combining all aspects of sustainability in a large scale supply chain considering master planning.
- Considering more real case constraints according to the novel case study.
- Supposing a new chemical process application that covers such rareness in applications.
- Addressing operational and tactical supply chain planning decisions under the sustainability paradigm.
- Extend previous models to multi-period, multi-product and considering inventory costs.

## 3. Problem description and integrated mathematical model

This problem considers in a sustainable supply chain management in all dimensions simultaneously. As mentioned before, sustainable development has three main pillars. By considering environmental and social objectives for each supply chain in addition to economic objective, it would be a sustainable supply chain. In this paper, we consider three environmental objectives, namely GHG emissions, consumed energy and generated wastes. Two social objectives are considered as the total travel distance of employees and total number of hires and lay-offs. For the economic objective, we have to integrate three subset of planning problems, namely (1) choosing suppliers and order lot-sizing. (2) planning the firm's production, and (3) planning the distribution procedure of final products.

Our objective is to look for the best decisions of planning for the following subjects:

- Purchasing plan: Determining the quantity of each raw material from each supplier that should be bought in each period.
- Supplying plan: Determining the quantity of each item from each supplier that should be supplied in each period.
- Producing plan: Determining the quantity of each final product that should be produced in each period.
- Distributing plan: Determining the quantity of each final product that should be transferred to each warehouse in each period.

### *3.1. Assumptions*

The main model assumptions are listed below:

- Based on the contract, Nashtarood is self-responsible for shipping costs of purchased woods to MWPI.
- There isn’t any unusable wood between purchased forest woods and imported ones.
- Every unit of woods, pulps and papers are ton.
- Every supplier has a portion of total company supplying constantly.

- The capacity of supplying wood from forests is limited.
- The imported woods are not debarked in wood and chip handling plant.
- The yard on the whole is divided to six sections: unusable, non-standard and standard (Hornbeam, Beech, Mixed species and imported woods).
- PM 2 produces two kinds of fluting papers: scf-0 (30%) and scf-20 (70%).
- The scf-20 one of fluting just needs the recycled pulp.
- There are 5 warehouses in the whole country as distribution centers (i.e., Tehran, Tabriz, Mashhad, Ahvaz and Bandar Abbas).

### *3.2. Parameters and decision variables*

**Set:**

| | |
|---|---|
| $i$ | index of supplied forest woods ($i$ = 1, . . .,4) |
| $j$ | index of purchased forest woods ($j$ = 1, 2, 3) |
| $k$ | index of imported forest woods ($k$ = 1, 2) |
| $l$ | index of supplied forest woods species ($l$ = 1, 2, 3) |
| $m$ | index of purchased forest woods species ($m$ = 1, . . ., 6) |
| $n$ | index of suppliers ($n$ = 1, . . ., 9) |
| $p$ | index of distribution centers ($p$ = 1, . . ., 5) |
| $q$ | index of final products ($q$ = 1, 2, 3) |
| $t$ | index of time periods ($t$ = 1, . . ., 12) |
| $r$ | index of regions ($r$ = 1, 2, 3) |
| $u$ | index of fluting paper ($u$ = 1, 2) |
| $v$ | index of importing pulp ($v$ = 1, 2) |

**Parameters:**

| | |
|---|---|
| $cs_{il}$ | unit cutting cost of forest wood $i$ of wood species $l$ |
| $cp_{jm}$ | unit purchasing cost of forest wood $j$ wood species $m$ |
| $ci$ | unit importing cost of forest woods |
| $css_{ln}$ | unit shipping cost of supplied forests' woods of species wood $l$ from supplier $n$ |
| $cps_{mn}$ | unit shipping cost of purchased forests' woods of species wood $m$ from supplier $n$ |
| $cis_n$ | unit shipping cost of imported forests' woods from supplier $n$ |
| $cso$ | unit slicing cost of oversize woods ($l > 2$ or $d > 80$ or knotted woods) |
| $cdc$ | unit debarking and chipping cost of woods |
| $cch$ | unit chipping cost of woods |
| $cpn$ | unit producing newsprint pulp cost |
| $cpf_u$ | unit producing fluting pulp $u$ cost |
| $cpa$ | unit packing cost |
| $cds_p$ | unit shipping cost to distribution center $p$ |
| $cin$ | unit inventory holding cost |
| $rsn_q$ | unit price of product $q$ |
| $rwg$ | unit price of grade 1 woods |
| $rwd$ | unit price of decayed woods |
| $rdl$ | unit price of debarking and chipping losses (supplied and purchased woods) |

| | |
|---|---|
| $rcl$ | unit price of chipping losses (only imported woods) |
| $l$ | portion of usable woods |
| $e$ | portion of standard supplied woods |
| $f$ | portion of standard purchased woods |
| $g$ | portion of non-standard supplied woods |
| $h$ | portion of non-standard purchased woods |
| $i$ | portion of unusable supplied woods |
| $j_n$ | portion of supply/purchase/import woods from supplier *n* |
| $ysc_{ij}$ | yard capacity for standard wood *i* of wood species *j* |
| $yic_k$ | yard capacity for importing wood *k* |
| $ync$ | yard capacity for non-standard woods |
| $yuc$ | yard capacity for unusable woods |
| $k$ | portion of importing budget for wood |
| $mb$ | monthly budget for importing |
| $ssc_{ilt}$ | supplying capacity of every supplier for forest wood *i* of wood species *l* in period *t* |
| $cch$ | chipping system capacity per hour |
| $mp_t$ | production time per month t |
| $qw_k$ | required quality of *k* imported wood chips in the CMP process |
| $qc_{ij}$ | required quality of *i* forest wood chips of *j* species in the CMP and NSSC processes |
| $pf_i$ | portion of forest wood *i* chips usage in the CMP and NSSC processes |
| $qnp$ | quantity of chips required to produce one unit newsprint pulp |
| $qfp$ | quantity of chips required to produce one unit fluting pulp |
| $cmc$ | CMP process capacity per hour |
| $nsc$ | NSSC process capacity per hour |
| $pnp$ | portion of newsprint pulp usage in PM1 |
| $pfp$ | portion of fluting pulp usage in PM2 |
| $pwp$ | portion of white imported pulp usage in PM1 |
| $pbp$ | portion of brown imported pulp usage in PM2 |
| $qnsp$ | quality of PM1 inputs to produce one unit newsprint paper |
| $qflp$ | quality of PM2 inputs to produce one unit fluting paper |
| $cip_v$ | unit importing cost of pulp *v* |
| $p_u$ | portion of producing fluting paper *u* in PM2 |
| $d_{qpt}$ | demand of final product *q* at the distribution center *p* in period *t* |
| $pgw$ | portion of grade 1 woods |
| $pdw$ | portion of decayed woods |
| $pwd$ | portion waste of debarking and chipping system |
| $pwc$ | portion waste of chipping system |
| $EPH$ | environmental impact of producing one unit output of chips & handling plant |
| $EPP$ | environmental impact of producing one unit output of pulp plant |
| $EPR$ | environmental impact of producing one unit output of paper machine plant |
| $EPT$ | environmental impact of transportation one unit final product to the distribution centers |
| $PRH$ | processing time of producing one unit output of chips & handling plant |

| | |
|---|---|
| $PRP$ | processing time of producing one unit output of pulp plant |
| $PRM$ | processing time of producing one unit output of paper machine plant |
| $ENH$ | energy use per hour for producing one unit output of chips & handling plant |
| $ENP$ | energy use per hour for producing one unit output of pulp plant |
| $ENM$ | energy use per hour for producing one unit output of paper machine plant |
| $WAH$ | mean generated waste for producing one unit output of chips & handling plant |
| $WAP$ | mean generated waste for producing one unit output of pulp plant |
| $WAM$ | mean generated waste for producing one unit output of paper machine plant |
| $\boldsymbol{dis_r}$ | distance between region *r* and company |
| $\boldsymbol{Lab_r^{int}}$ | primary amount of employees live in region *r* and work in company in period *t* |
| $cap_t$ | maximum number of hours that an employee could work during period *t* |
| $\boldsymbol{LabCap_r}$ | amount of employees ready for work in region *r* in period *t* |

**Decision variables:**

| | |
|---|---|
| $X_{ilnt}$ | supplying quantity of forest wood *i* of wood species *l* from supplier *n* in period *t* |
| $Y_{jmnt}$ | purchasing quantity of forest wood *j* of wood species *m* from supplier *n* in period *t* |
| $Z_{knt}$ | importing quantity of forest wood *k* from supplier *n* in period *t* |
| $I_{ijt}$ | ending inventory level of forest wood *i* of wood species *j* in period *t* |
| $F_t$ | ending inventory level of firewood in period *t* |
| $V_{kt}$ | ending inventory level of imported forest wood *k* in period *t* |
| $CM_{ijt}$ | chips quantity of forest wood *i* of wood species *j* for the CMP process in period *t* |
| $NS_{ijt}$ | chips quantity of forest wood *i* of wood species *j* for NSSC process in period *t* |
| $NSF_t$ | chips quantity of firewood for the NSSC process in period *t* |
| $W_{kt}$ | chips quantity of imported forest wood *k* for the CMP process in period *t* |
| $A_{vt}$ | importing quantity of pulp *v* using for paper machine in period *t* |
| $Wg_t$ | quantity of grade 1 woods in period *t* |
| $Wd_t$ | quantity of decayed woods in period *t* |
| $Ld_t$ | quantity of debarking losses in period *t* |
| $Lc_t$ | quantity of chipping losses in period *t* |
| $NP_t$ | pulp quantity of newsprint in period *t* |
| $NF_{ut}$ | pulp quantity of fluting *u* pulp in period *t* |
| $FP_t$ | paper quantity of newsprint in period *t* |
| $FF_{ut}$ | paper quantity of fluting *u* in period *t* |
| $S_{qpt}$ | shipping quantity of final product *q* to distribution center *p* in period *t* |
| $\boldsymbol{Lab_{rt}}$ | amount of employees live in region *r* and work in company in period *t* |
| $\boldsymbol{LH_{rt}}$ | amount of employees live in region *r* hired by company in period *t* |
| $\boldsymbol{LF_{rt}}$ | amount of employees live in region *r* laid-off by company in period *t* |

*3.3. Proposed mathematical model*

Based on the above-mentioned assumptions and descriptions, we develop the following multi-objective linear mathematical model for a multi-echelon, multi-product, multi-period supply chain planning.

*3.3.1 Objective functions*

The formulation of all six objectives of the model is presented as follows:

$$\text{Max} \quad \text{OF1} = TRS - (TCO + TCP + TCD) \tag{1}$$

$$\begin{aligned}\text{Max} \quad \text{OF1} = & \sum_{t}[(\sum_{p,q} rsn_q.S_{qpt}) + rwg.Wg_t + rwd.Wd_t + rdl.Ld_t + rcl.Lc_t] \\ & -\{\sum_{t,n,i,l}(cs_{il} + css_{ln}).X_{ilnt} + \sum_{t,n,j,m}(cp_{jm} + cps_{mn})Y_{jmnt} + \sum_{t,k,n}(ci + cis_n).Z_{knt} \\ & + \sum_{t,v} cip_v.A_{vt} + cso.[(0.06).\sum_{t,n,i,l} X_{ilnt} + (0.01).\sum_{t,n,j,m} Y_{jmnt}] + cdc.(\sum_{i,j,t} CM_{ijt} + \sum_{i,j,t} NS_{ijt} \\ & + \sum_{t} NSF_t) + cch.\sum_{k,t} W_{kt} + cpn.\sum_{t} NP_t + \sum_{u,t} cpf_u.NF_{ut} + cpa.(\sum_{t} FP_t + \sum_{u,t} FF_{ut}) \\ & + cin.(\sum_{i,j,t} I_{ijt} + \sum_{t} F_t + \sum_{k,t} V_{kt}) + \sum_{q,p} cds_p.S_{qpt}\}\end{aligned} \tag{2}$$

$$\begin{aligned}\text{Min} \quad \text{OF2} = & EPH.\sum_{i,j,t}(CM_{ijt} + NS_{ijt} + NSF_t) + EPP.\sum_{u,t}(NP_t + NF_{ut}) \\ & + EPM.\sum_{u,t}(FP_t + FF_{ut}) + EPT.\sum_{q,p,t} S_{qpt}\end{aligned} \tag{3}$$

$$\begin{aligned}\text{Min} \quad \text{OF3} = & PRH.ENH.\sum_{i,j,t}(CM_{ijt} + NS_{ijt} + NSF_t) + PRP.ENP.\sum_{u,t}(NP_t + NF_{ut}) \\ & + PRM.ENM.\sum_{u,t}(FP_t + FF_{ut})\end{aligned} \tag{4}$$

$$\begin{aligned}\text{Min} \quad \text{OF4} = & WAH.\sum_{i,j,t}(CM_{ijt} + NS_{ijt} + NSF_t) \\ & + WAP.\sum_{u,t}(NP_t + NF_{ut}) + WAM.\sum_{u,t}(FP_t + FF_{ut})\end{aligned} \tag{5}$$

$$\text{Min} \quad \text{OF5} = \sum_{r,t} dis_r.Lab_{rt} \tag{6}$$

$$\text{Min} \quad \text{OF6} = \sum_{r,t}(LH_{rt} + LF_{rt}) \tag{7}$$

Objective function OF1 (1) and (2) are to maximize the total profits of the company. The total profits of the company include the total selling revenues (TRS) and total cost of logistics. The total costs of logistics include the total costs of ownership (TCO), total costs of production (TCP) and total costs of distribution (TCD). Objective function OF2 (3) minimizes total GHG emissions of the supply chain in production and transportation phases. Objective function OF3 (4) minimizes total consumed energy all over production stages. Objective function OF4 (5) minimizes total generated wastes throughout production plants. Objective function OF5 (6) minimizes total travel distance of employees with the aim of improving local development. The nearness of employees to firm indicates local employment plus employee welfare, e.g. by decreasing the time needed to spend in personal or public transportation mode. Objective function OF6 (7) in order to raise the employment consistency, minimizes total amount of hires and lay-offs. Objective function OF1 is an economic objective. Objective functions OF2, OF3 and OF4 are environmental objectives. Objective functions OF5 and OF6 are social objectives.

*3.3.2 Constraint sets*

(I) Inventory level constraints: All relevant balancing constraints of inventory at wood and chip handling plant are illustrates as follows:

$$I_{ij,t-1} + l.\sum_{n} X_{ilnt} + \sum_{n} Y_{jmnt} - I_{ijt} = CM_{ijt} + NS_{ijt} \tag{8}$$

$$F_{t-1} + l.\sum_{n} X_{ilnt} + \sum_{n} Y_{jmnt} - F_{t} = NSF_{t} \tag{9}$$

$$V_{k,t-1} + \sum_{n} Z_{knt} - V_{kt} = W_{kt} \tag{10}$$

Constraint (8) represents a balancing equation for Hornbeam and Beech forest woods inventory. Constraint (9) represents balancing equation for mixed species and Persian Iron Wood forest wood inventory. Constraint (10) is about firewood inventory of every species and the last, for imported woods inventory.

(II) Yard of handling plant capacity constraints: The yard is limited to three generally sections for storing woods; standard, non-standard and unusable woods. The constraints summarized as follows:

$$e.\sum_{n} X_{ilnt} + f.\sum_{n} Y_{jmnt} \le ysc_{ij} \tag{11}$$

$$g.\sum_{i,l,n} X_{ilnt} + h.\sum_{j,m,n} Y_{jmnt} \le ync \tag{12}$$

$$i.\sum_{n} X_{ilnt} \le yuc \tag{13}$$

$$\sum_{n} Z_{knt} \le yic_{k} \tag{14}$$

Constraint (11) is the yard capacity for standard woods. Constraint (12) is the yard capacity for non-standard woods. Constraint (13) is the yard capacity for unusable woods. Constraint (14) is the yard capacity for imported forests' woods.

(III) Supplying woods proportion constraints: There are different portions for supplying woods included supply, purchase and import woods from every supplier. The constraints are summarized as follows:

$$X_{ilnt} \leq j_n . \sum_n X_{ilnt} \tag{15}$$

$$Y_{jmnt} \leq j_n . \sum_n Y_{jmnt} \tag{16}$$

$$Z_{knt} \leq j_n . \sum_n Z_{knt} \tag{17}$$

Constraint (15) represents the supply portion of the woods. Constraint (16) represents the purchase portion of the woods. Constraint (17) represents the import portion of the woods.

(IV) Importing budget constraint: We have a limited budget for importing woods and pulps in MWPI:

$$ci . \sum_{n,k} Z_{knt} \leq k .mb \tag{18}$$

$$ci . \sum_{n,k} Z_{knt} + \sum_v cip_v .A_{vt} \leq mb \tag{19}$$

Constraint (18) is the budget limitation of importing woods and Constraint (19) is the budget limitation of importing pulp.

(V) Supply capacity constraint: The supplying capacity of supplied forest woods from each supplier is limited:

$$\sum_n X_{ilnt} \leq ssc_{ilt} \tag{20}$$

Constraint (20) shows the limitation of supplying capacity of each supplier.

(VI) Chipping system capacity constraint: The chipping system capacity is limited:

$$\sum_{i,j} CM_{ijt} + \sum_{i,j} NS_{ijt} + NSF_t + \sum_k W_{kt} \leq chc.mp_t \tag{21}$$

Constraint (21) represents the chipping system capacity.

(VII) Pulp processes capacity constraint: The pulp plant has limited capacity for both CMP and NSSC processes:

$$NP_t \leq cmc.mp_t \tag{22}$$

$$\sum_u NF_{ut} \leq nsc.mp_t \tag{23}$$

Constraint (22) represents the CMP pulp process's capacity and constraint (23) represents the NSSC pulp process's capacity.

(VIII) Mixture constraints: Based on BOM, there are specific portions for mixing some wood chips in pulp plant:

$$CM_{ijt} = qc_{ij}.\sum_{i,j} CM_{ijt} \tag{24}$$

$$NS_{ijt} = qc_{ij}.\sum_{i,j} NS_{ijt} \tag{25}$$

$$FF_{ut} \leq p_u.\sum_u FF_{ut} \tag{26}$$

Constraints (24) and (25) are mixture constraints. Constraint (26) represents the fluting papers' portions of production.

(IX) Balancing constraints: The balancing constraints in pulp plant are summarized as follows:

$$\sum_{i,j} pf_i + CM_{ijt} + (1 - \sum_i pf_i) \sum_k W_{kt} = qnp.NP \tag{27}$$

$$\sum_{i,j} pf_i + NS_{ijt} + (1 - \sum_i pf_i) \sum_k NSF_t = qfp.NF_{ut} \tag{28}$$

The balancing constraints in paper machines plant are summarized as follows:

$$pnp.NP_t + pwp.A_{vt} = qnsp.FP_t \tag{29}$$

$$pfp.NF_{ut} + pbp.A_{vt} = qflp.\sum_u FF_{ut} \tag{30}$$

The balancing constraints in packaging plant are summarized as follows:

$$FP_t = \sum_p S_{1pt} \tag{31}$$

$$FF_{1t} = \sum_p S_{2pt} \tag{32}$$

$$FF_{2t} = \sum_p S_{3pt} \tag{33}$$

The balancing constraints for clearing the situation of some dependent variables are represented below:

$$Wg_t = pgw.\sum_{i,l,n} X_{ilnt} \tag{34}$$

$$Wd_t = pdw.\sum_{i,l,n} X_{ilnt} \tag{35}$$

$$Ld_t = pwd.(\sum_{i,j} CM_{ijt} + \sum_{i,j} NS_{ijt} + NSF_t) \tag{36}$$

$$Lc_t = pwc.\sum_{k} W_{kt} \tag{37}$$

(X) Demand constraint: Demand constraint among different distribution centers and for all products in every month is represented as follows:

$$S_{qpt} \geq d_{qpt} \tag{38}$$

(XI) Social constraints: Total amount of employees laid-off should not transcend the amount of employees working within a period:

$$LF_{r1} \leq Lab_r^{\text{int}} \tag{39}$$

$$LF_{rt} \leq Lab_{r,(t-1)} \tag{40}$$

Total amount of employees lives in region *r* and work in company at period *t*:

$$Lab_{r1} \leq Lab_r^{\text{int}} + LH_{r1} - LF_{r1} \tag{41}$$

$$Lab_{rt} \leq Lab_{r,(t-1)} + LH_{rt} - LF_{rt} \tag{42}$$

The amount of employees live in region *r* and work in company at period *t* should not transcend the total amount of employees that are ready for work from that region:

$$Lab_{rt} \leq LabCap_r \tag{43}$$

The amount of employees hired from a region should not transcend the total amount of employees that are ready for work from that region:

$$LH_{rt} \leq LabCap_r \tag{44}$$

The amount of employees needed should supply the whole workload within each period:

$$\sum_{r} Lab_{rt} = \frac{PRH}{Cap_t} . \sum_{i,j,t} (CM_{ijt} + NS_{ijt} + NSF_t)$$
$$+ \frac{PRP}{Cap_t} . \sum_{u,t} (NP_t + NF_{ut}) + \frac{PRM}{Cap_t} . \sum_{u,t} (FP_t + FF_{ut}) \quad (45)$$

**4. Case study**

Mazandaran pulp and paper industry (MWPI) is the biggest firm producing pulp and paper in the Middle East. This company was founded in 1996 and supplied by the first class European machines of paper and pulp. MWPI has the capacity of producing 175000 tons per year. This firm has two pulping production lines of chemical mechanical pulp (CMP) and neutral sulphite semi-chemical (NSSC) as well as two paper machines in width of 440 cm and 610 cm. MWPI produces newsprint, wood-container printing & writing, and semi-chemical fluting paper and board. It sustains great communication with customers in native and international markets, such as CIS countries, Africa, Middle East, and Far East with a strong focus on innovation and contiguous progress in quality and environment safekeeping.

MWPI is located in north of Iran, which supplied from a predesignated set of suppliers (e.g., West of Haraz, Talar, Tajan, Gorgan, Tonekabon, Nowshahr and Nashtarood). The final products are eventually delivered to different warehouses (i.e., Tehran, Tabriz, Mashhad, Ahvaz and Bandar Abbas) to satisfy their demands. The process of producing paper in the MWPI is simplified in Fig. 1.

{Please insert Fig. 1 about here.}

Plant 300: Wood and Chip Handling Plant
Plant 400: Pulp Plant
Plant 500: Steam Plant
Plant 600: Paper Machine Plant
Plant 650: Packaging Plant

Woods from forest or some external suppliers store in plant 300. Then, they will be transferred to plant 400 for transforming to pulp and in plant 500 that they will be steamed. In plant 600 the provided pulp will transform to paper roles and will be cut and filled in packages finally in plant 650.

There are some assumptions with exact values due to the case study:

- Standard wood measures:
  Length: 2 - 6 meter, diameter: 10 - 80 centimetre
- The maximum importing budget is 12 million dollars in each year that 67% of it is for woods.
- Based on historical data, 5% of any supplied forest woods is unusable; 2% grade 1 wood and 3% decayed wood.
- Based on historical data, 6% of supplied forest woods and 1% of purchased forest woods are oversize (longer than 6 meter or thicker than 80 centimetre or knotted woods).

- The imported woods are used by minimum 80% of birch and maximum 20% of aspen in wood and chip handling plant.
- The yard of storing woods is 80000 $m^2$ and the maximum height of storing woods in yard limited to three meters, because of transporting limitations.
- Maximum space for unusable woods in yard is 2% and for non-standard woods is 10%.
- The maximum input capacity of chippers is 190 cubic meters per hour; it's equivalent to 136 tons per hour.
- The wood and chip handling plant has 96.4% efficiency; 0.6% wastes for debarking system and 3% waste for chipping system.
- The chipping system's capacity is 136 tons per hour.
- The maximum input capacity of the CMP process is 310 tons newsprint pulp in one day (12.92 ton per hour).
- The maximum input capacity of the NSSC process is 300 tons newsprint pulp in one day (12.50 ton per hour).
- Maximum 20% Aspen and minimum 80% Birch is mixed in CMP process.
- Based on BOM (Bill of Materials), sequentially 0.7, 0.3, 0.75, 0.25, 0.4, 0.6, 0.3, 0.7 mixture of Hornbeam, Beech, Mixed species and Persian Iron Wood – both log and cuttine – needed for CMP and NSSC processes incomes.
- The efficiency of the CMP and NSSC processes are 85% and 75%, respectively.
- It uses 106 kilograms liquor for per ton of output newsprint pulp.
- It uses 120 kilograms liquor for per ton of output fluting pulp.
- The efficiency of PM1 (Paper machine for producing newsprint paper, and writing and printing paper) is 89% and for PM2 (Paper machine for producing fluting paper) is 117% {Per one unit input in PM2 we'll have 1.17 unit output}.
- Based on BOM, sequentially 0.83 and 0.17 mixtures of CMP pulp and white imported pulp is needed for PM1 and for PM2, 0.95 and 0.05 of NSSC pulp and brown imported pulp is needed.
- The scf-0 one of fluting needs 40 kilogram imported pulp per unit and 30 kilogram recycled pulp per unit in PM 2.
- There is a fixed time for production each month. Table 2 shows production time per month in hours.

{Please insert Table 2 about here.}

## 5. Solution methodology

To solve multi-objective models, several approaches have been proposed in the literature as we have reviewed in prior sections. An improved version of the augmented ε-constraint method (AUGMECON2) is used for the proposed model. The ε-constraint method has a lot of benefits. The ε-constraint method is a generation method that all the efficient solutions of the problem are generated first and afterwards the decision maker is free to select among them, the most preferred one by her/his attitude. In case that decision maker is unavailable or scarcely available and interaction is tough, they are desirable as the decision maker will just participate in the second step. In addition, when none of the possible results has been left undiscovered, it fortifies confidence of decision maker to find the final decision.

The solution methodology as given by Mavrotas and Florios (2013) is summarized below:

In the original AUGMECON method given by Mavrotas (2009) the problem solved is shown below:

$$\text{Max } (f_1(x) + eps \times (S_2/r_2 + S_3/r_3 + \cdots + S_p/r_p))$$

s.t.

$$f_2(\text{x}) - S_2 = e_2$$

$$f_3(\text{x}) - S_3 = e_3$$

. . .

$$f_p(\text{x}) - S_p = e_p$$

$$x \in S \quad and \quad S_i \in R^+$$

where $e_2$, $e_3$, …, $e_p$ are the parameters for the RHS for the specific iteration drawn from the grid points of the objective functions 2, 3, …, *p*. The parameters $r_2$, $r_3$, …, $r_p$ are the ranges of the respective objective functions. $S_2$, $S_3$, …, $S_p$ are the surplus variables of the respective constraints and $\text{eps} \in [10^{-6}, 10^{-3}]$.

In AUGMECON2 as an improved version of AUGMECON, Mavrotas and Florios (2013) slightly modify the objective function as follows:

$$\text{Max } (f_1(x) + eps \times (S_2/r_2 + 10^{-1} \times S_3/r_3 + \cdots + 10^{-(p-2)} \times S_p/r_p))$$

This modification is done in order to perform a kind of lexicographic optimization on the rest of the objective functions if there are any alternative optima. For example, with this formulation the solver will find the optimal for $f_1$ and then it will try to optimize $f_2$, then $f_3$ and so on. With the previous formulation, the sequence of optimizations of $f_2$-$f_p$ was indifferent, while we now force the sequential optimization of the constrained objective functions (in case of alternative optima).

For each objective function (2, …., *p*), we calculate the objective function range. Then we divide the range of the *k*-th objective function to $q_k$ equal intervals using ($q_k$ - 1) intermediate equidistant grid points. Thus we have in total ($q_k$ + 1) grid points that are used to vary parametrically the RHS ($e_k$) of the *k*-th objective function. The total number of runs becomes ($q_2$ + 1) × ($q_3$ + 1) × … × ($q_p$ + 1). Let $r_k$ be the range of the objective function *k* (*k* = 2, …, *p*). Then the discretization step for this objective function is given by:

$$step_k = r_k / q_k$$

The RHS of the corresponding constraint in the *t*-th iteration in the specific objective function will be as follows:

$$e_{kt} = f\ \text{min}_k + t \times step_k$$

where $f\ \text{min}_k$ is the minimum from the pay-off table and *t* is the counter for the specific objective function.

In each iteration, we check the surplus variable that corresponds to the innermost objective function. In this case, it is the objective function with *p*=2. Then we calculate the *bypass coefficient* as follows:

$$b = \text{int}(S_2 / step_2)$$

where int () is the function that returns the integer part of a real number. When the surplus variable $S_2$ is larger than $step_2$, it is implied that in the next iteration the same solution will be obtained with the only difference being the surplus variable which will have the value $S_2$-$step_2$. This makes the iteration redundant, and therefore we can bypass it as no new Pareto-optimal solution is generated. The bypass coefficient *b* actually indicates how many consecutive iterations we can bypass.

## 6. Experiments and numerical results

The aim of this section is to remark how the mentioned approach will aid the decision maker perceiving and making trade-offs regarding to the three sustainability pillars of the model. According to the previous studies and sections, we design our paper to consider six objective functions simultaneously as a novel approach in the context of sustainable supply chain management:

- Overall supply chain profit
- Total generated GHG emissions
- Total consumed energy
- Total generated wastes
- Total travel distance of employees
- Total amount of employees would be hired and laid-off

Our mathematical model is solved according to the wood and paper industries case presented in Section 3. By purpose of displaying the applicability of the presented model and methods of relevant references, the improved version of the augmented ε-constraint method is coded in the GAMS software to solve the complete case of the problem contained almost 2000 variables and 4000 constraints. GAMS (ver. 24.1.2) using the CPLEX solver is able to solve MILP models. The PC with Intel® Core™ i7-4702| processor, 2.2 GHz, 6 GB of RAM, and the Windows 8 operating system is utilized as a technical platform.

Table 3 shows the instance solution with overall SC profit in Rials, GHG emissions in Kg, consumed energy in KW-h, generated wastes in unit, traveled distance of employees in Km, and hires and lay-offs of employees in a number of people.

{Please insert Table 3 about here.}

Fig. 2 shows the Pareto solutions in various iterations. The overall SC profit has a tendency to increase; however, the other objective functions have mixed tendencies, either to increase or decrease. As a result, it depends on the decision maker's attitude to select the best result in his/her point of view. In Fig. 2, the overall SC profit is multiplied by $10^{-8}$, consumed energy is multiplied by $10^{-11}$, generated wastes are multiplied by $10^{-3}$ and travel distance of employees is multiplied by $10^{-2}$. Table 4 illustrates the corresponding results to Fig. 2 as well.

Based on the detailed results, the decision maker has a variety of choices for choosing the best solution. All the values of objective functions should be considered simultaneously whether they are maximum or minimum. For example, in iteration 18, the overall profit of the supply chain is 18135767600000 with 31474.921 kg of GHG emissions generated, 2132480000000 MW-h energy used, 14407958.10 unit wastes generated, 1672948.85 km travel distance by employees and 10597 number of hires and lay-offs of employees totally.

{Please insert Fig. 2 about here.}
{Please insert Table 4 about here.}

In addition, Fig. 3(a, b, c) and 4(a, b, c) depict the values of the objective functions of Pareto solutions three by three. As a consequence, it can be realized that the results of operating diverse objective functions are not inevitably stable, and hence the objective functions should be taken in to account apart. Fig. 3(a) shows surface plot of three objective functions namely, consumed energy vs generated GHG emissions and SC profit. Fig. 3(b) shows surface plot of three objective functions namely, generated wastes vs generated GHG emissions and SC profit. Fig. 3(c) shows surface plot of three objective functions namely, hires and lay-offs vs travel distance and SC profit. Fig. 4(a) shows a contour plot of three objective functions namely, consumed energy vs generated GHG emissions and SC profit. Fig. 4(b) shows a contour plot of three objective functions namely, generated wastes vs generated GHG emissions and SC profit. Fig. 4(c) shows a contour plot of three objective functions namely, hires and lay-offs vs travel distance and SC profit.

{Please insert Fig. 3 about here.}
{Please insert Fig. 4 about here.}

## 7. Conclusions

An integrated approach for applying sustainable development axioms to supply chain planning models has been proposed in this paper. Contrary to increasing interest for mathematical modeling of sustainable supply chains, comprehensive approaches considering the application of the three pillars (i.e., economy, environment and society) are very rare yet. Based on our detailed literature review, we created an approach that combines sustainability criteria with the supply chain decisions in the context of supply chain management and supply chain master planning. By linking this approach to mathematical programming, the environmental, economic and social impacts could all be simultaneously combined. Indeed, for a multi-product, multi-echelon, multi-period supply chain planning, we formulated a multi-objective linear programming model. Additionally, we considered and solved the wood and paper industries case by using an improved version of the augmented ε-constraint method (AUGMECON2). We showed by analyzing the results, how the Pareto solutions could be used by the decision maker to aid her/him in selecting the supply chain plans that collates best her/him aims and traits in terms of environmental, economic and social performances. In our future work, we aim to deepen our research on finding and defining new social factors that have significant roles in supply chains.

**References**


Ashby, A., Leat, M. & Hudson-Smith, M., (2012). Making connections: a review of supply chain management and sustainability literature. *Supply Chain Management: An International Journal*, 17(5), 497-516.

Awudu, I. & Zhang, J., (2012). Uncertainties and sustainability concepts in biofuel supply chain management: A review. *Renewable and Sustainable Energy Reviews*, 16(2), 1359–1368.

Boukherroub, T., Ruiz, A., Guinet, A. & Fondrevelle, J., (2014). An integrated approach for sustainable supply chain planning. *Computers & Operations Research*, 54, 180–194.

Brandenburg, M., Govindan, K., Sarkis, J. & Seuring, S., (2014). Quantitative models for sustainable supply chain management: Developments and directions. *European Journal of Operational Research*, 233(2), 299–312.

Chaabane, A., Ramudhin, A. & Paquet, M., (2012). Design of sustainable supply chains under the emission trading scheme. *International Journal of Production Economics*, 135(1), 37–49.

Devika, K., Jafarian, A. & Nourbakhsh, V., (2014). Designing a sustainable closed-loop supply chain network based on triple bottom line approach: A comparison of metaheuristics hybridization techniques. *European Journal of Operational Research*, 235(3), 594–615.

Entezaminia, A., Heydari, M. & Rahmani, D., (2016). A multi-objective model for multi-product multi-site aggregate production planning in a green supply chain: Considering collection and recycling centers. *Journal of Manufacturing Systems*, 40, 63–75.

Fahimnia, B., Sarkis, J. & Eshragh, A., (2015). A tradeoff model for green supply chain planning: A leanness-versus-greenness analysis. *Omega*, 54, 173–190.

Govindan, K. et al., (2014). Two-echelon multiple-vehicle location-routing problem with time windows for optimization of sustainable supply chain network of perishable food. *International Journal of Production Economics*, 152, 9–28.

Jindal, A. & Sangwan, K.S., (2016). Multi-objective fuzzy mathematical modelling of closed-loop supply chain considering economical and environmental factors. *Annals of Operations Research*. 1-26.

Luthra, S., Garg, D. & Haleem, A., (2014). Green Supply Chain Management - Review.pdf. *Journal of Advances in Management Research*, 11(1), 20–46.

Mavrotas, G. & Florios, K., (2013). An improved version of the augmented ε-constraint method (AUGMECON2) for finding the exact pareto set in multi-objective integer programming problems. *Applied Mathematics and Computation*, 219(18), 9652–9669.

Mavrotas, G. (2009). Effective implementation of the ε-constraint method in multi-objective mathematical programming problems. *Applied Mathematics and Computation*, 213, 455–465.

Mavrotas, G., Skoulaxinou, S., Gakis, N., Katsouros, V. & Georgopoulou, E. (2013). A multi-objective programming model for assessment the GHG emissions in MSW management. *Waste Management*, 33(9), 1934–1949.

Mousazadeh, M., Torabi, S.A. & Pishvaee, M. S., (2014). Green and Reverse Logistics Management Under Fuzziness. *Studies in Fuzziness and Soft Computing*, 313, 517–551.

Palak, G., Ekşioğlu, S.D. & Geunes, J., (2014). Analyzing the impacts of carbon regulatory mechanisms on supplier and mode selection decisions: An application to a biofuel supply chain. *International Journal of Production Economics*, 154, 198–216.

Pishvaee, M.S. & Razmi, J., (2012). Environmental supply chain network design using multi-objective fuzzy mathematical programming. *Applied Mathematical Modelling*, 36(8), 3433–3446.

Pishvaee, M.S., Razmi, J. & Torabi, S.A., (2014). An accelerated Benders decomposition algorithm for sustainable supply chain network design under uncertainty: A case study of medical needle and syringe supply chain. *Transportation Research Part E: Logistics and Transportation Review*, 67, 14–38.

Pishvaee, M.S., Torabi, S.A. & Razmi, J., (2012). Credibility-based fuzzy mathematical programming model for green logistics design under uncertainty. *Computers and Industrial Engineering*, 62(2), 624–632.

Saffar, M.M., G, H.S. & Razmi, J., (2015). A new multi objective optimization model for designing a green supply chain network under uncertainty. *International Journal of Industrial Engineering Computations*, 6, 15–32.

Saffari, H., Makui, A., Mahmoodian, V. & Pishvaee, M.S., (2015). Multi-objective robust optimization model for social responsible closed-loop supply chain solved by non-dominated sorting genetic algorithm. *Journal of Industrial and Systems Engineering*, 8(3), 42-59.

Sazvar, Z., S.M.J. Mirzapour Al-e-hashem, A. Baboli, M.R. Akbari Jokar, (2014). A bi-objective stochastic programming model for a centralized green supply chain with deteriorating products, In International Journal of Production Economics, 150, 140-154.

Seuring, S. & Müller, M., (2008). From a literature review to a conceptual framework for sustainable supply chain management. *Journal of Cleaner Production*, 16(15), 1699-1710.

Soysal, M., Bloemhof-Ruwaard, J.M. & Van Der Vorst, J.G.A.J., (2014). Modelling food logistics networks with emission considerations: The case of an international beef supply chain. *International Journal of Production Economics*, 152, 57–70.

Validi, S., Bhattacharya, A. & Byrne, P.J., (2014a). A case analysis of a sustainable food supply chain distribution system - A multi-objective approach. *International Journal of Production Economics*, 152, 71–87.

Validi, S., Bhattacharya, A. & Byrne, P.J., (2014b). A solution method for A two-layer sustainable supply chain distribution model. *Computers & Operations Research*, 54, 204-217.

You, F., Graziano, D.J. & Snyder, S.W., (2012). Optimal design of sustainable cellulosic biofuel supply chains: Multiobjective optimization coupled with life cycle assessment and input – output analysis. *AIChE Journal*, 58(4), 1157–1180.

Yu, H., S, W.D. & Solvang, B., (2016a). A multi-objective mathematical programming for sustainable reverse logistics network design - Part I: Model formulation. *WIT Transactions on Engineering Sciences*, 113, 287–295.

Yu, H., S, W.D. & Solvang, B., (2016b). A multi-objective mathematical programming for sustainable reverse logistics network design - Part II: Model application and analysis. *WIT Transactions on Engineering Sciences*, 113, 296–303.

Yue, D., Slivinsky, M., Sumpter, J. & You, F., (2014). Sustainable design and operation of cellulosic bioelectricity supply chain networks with life cycle economic, environmental, and social optimization. *Industrial and Engineering Chemistry Research*, 53(10), 4008–4029.