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Modeling and analysis of sustainable supply chain dynamics

Gang Wang[1] · Angappa Gunasekaran[2]

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Abstract This paper studies the dynamic behavior of the interaction between sustainable supply chains and environment. Environmental impact exists at each stage throughout supply chains such as resource extraction, production, distribution, repairs, and waste disposal, among others. As market and competition constantly change over time, however, supply chains interact significantly with environment, so managing supply chains sustainably is dynamic. In this paper, a mathematical model based on nonlinear dynamic system is presented to describe the dynamics of the impact of supply chains on environment while achieving sustainable supply chains. The existence and uniqueness of its solutions are proved, followed by the analysis on its equilibrium and stability. To better understand the dynamic mechanism of this proposed system, performance analysis is conducted with respect to three parameters: (a) design production capacity; (b) environmental cost; and (c) demand rate. Analytical results validate the dynamic interaction of supply chains with environment, and justify the environmental and economic significance of supply chain sustainability.

Keywords Sustainable supply chains · Complex dynamic system · Stability · Performance analysis

✉ Gang Wang
gwang1@umassd.edu

Angappa Gunasekaran
agunasekaran@umassd.edu

1 Department of Decision and Information Sciences, Charlton College of Business, University of Massachusetts Dartmouth, North Dartmouth, MA 02747, USA

2 Charlton College of Business, University of Massachusetts Dartmouth, North Dartmouth, MA 02747, USA

1 Introduction

Supply chains are connected networks that transform organizations' inputs into outputs. Supply chain operations start with human extraction of raw materials and continue with production, storage, and distribution before finally delivering to customers. Each stage in supply chains has the significant impact on environment. Traditionally, organizations have focused on supply chain efficiency and flexibility to improve customer service level and respond quickly to business challenges. However, increasing environmental pressures and growing expectations of customers and business partners on sustainable products have enabled organizations to see successful sustainable supply chain operations as a new measure of supply chain performance.

Supply chain sustainability is increasingly realized as a key component in gaining competitive advantage for organizations due to long-term environmental, social, and economic values it can create for all stakeholders and society (Rourke 2014). However, companies are lack of knowledge on the interaction between environment and supply chain systems during the life cycle of a product such that they fail to effectively measure and analyze the impact of supply chain operations on environment (Linton et al. 2007). Meanwhile, companies have received growing pressures from government regulations, competition, stakeholders, and supply chain risks, thus demanding more information on the interactive impact of supply chain systems on environment. Unfortunately, gaining such information from supply chain systems can be time-consuming, costly, and even impossible because supply chain operations involves continuously changing markets, competition, and environment, which results in the dynamic interaction between environment and supply chains (United Nations Global Compact 2014). Such dynamism of supply chains with environment brings about various challenges for integrating sustainability into supply chain operations. Therefore, there have been increasing needs for developing new tools to help decision makers better understand the dynamic characteristics of the interaction between supply chains and environment, and effectively manage the environmental impact of supply chain operations in the life cycle of a product.

This study was motivated by the dynamics of sustainable supply chain operations as above mentioned. At each stage of a product's life from natural resource extraction to end-of-life disposal, supply chains have dynamic impact on the environment. For instance, in apparel supply chains, the life cycle of an apparel product ranges from the production of natural and synthetic fibers, to the manufacture of a wide variety of semi-finished and finished products, to end-of-life management as shown in Fig. 1 below. Specifically, cotton production is resource-intensive. For example, the cotton used to produce one pair of jeans requires up to 10 tons of water. The use of harmful chemicals for producing fabrics and apparel products results in serious pollution on the environment. Frequent transportation for raw materials, fabrics, and finished products also contributes to heavy carbon dioxide emissions. Additionally, post-purchase laundering of clothing requires intense energy use, and especially products containing synthetic fibers decompose very slowly (Agbonkhese 2010). Furthermore, these negative environmental impacts increase operations costs and supply chain complexity, thereby mitigating the overall supply chain performance. Hence, a new model is needed to capture the dynamics of the complex interaction between environment and supply chains such that an effective management and control on the impact of supply chains on the environment can be achieved.

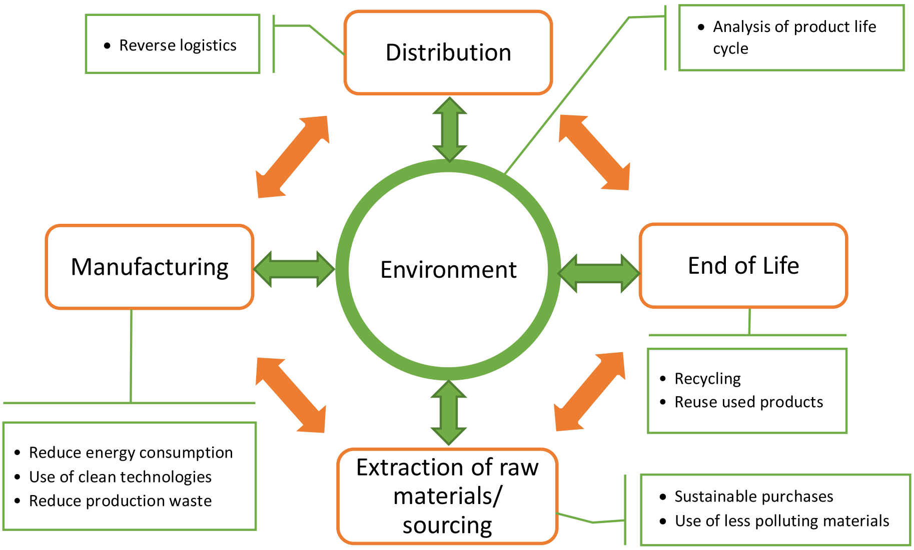

Fig. 1 Life cycle of an apparel product

Since supply chains interacting with environment are complex systems, this paper employs the concepts and techniques of nonlinear dynamic systems to describe the dynamic impact of supply chains on the environment. Seen as biological system, the entire supply chain systems use resources (i.e., raw materials, energy and water) from the environment to produce goods or services for the purpose of meeting customers' needs, and at the same time dispose waste into the environment (i.e., chemicals, end-of-life products, and polluted water). The environment has the reverse impact on supply chain systems similar to the organism-environment relationship in biological system. Microbial growth models are modified in this paper to capture the dynamic supply chain impact on the environment (Wang et al. 2007, 2008, 2009). The dynamics is reflected on the interaction of supply chain systems with the environment (Byrne et al. 2010).

To the best of our knowledge, this paper is the first among the literature to study the dynamic impact of sustainable supply chains on environment by nonlinear dynamic systems, although supply chain dynamics has been studied for decades. In this paper, a mathematical model is first presented to characterize the interaction of supply chain operations with the environment, according to the theory of nonlinear dynamic systems. Then mathematical analysis on the dynamic system is provided as the basis for the performance analysis of the system, i.e., the existence, uniqueness, and continuity of solutions on initial conditions, as well as the equilibrium and stability of this dynamic system. Finally, the dynamic performance of this system is evaluated in term of three parameters in this model, i.e., design production capacity, environmental cost, and demand rate. Simulation results show that the proposed dynamic system is well designed to capture the dynamics of environmental impact of supply chains. The main contribution of this model is to explicitly present the interaction of supply chains with environment rather than implicitly as in system dynamics and to facilitate the optimal control on supply chain operations which aims to minimize environmental impact.

The remainder of this paper is organized as follows: Sect. 2 includes a literature review of sustainable supply chain modelling. Section 3 presents a nonlinear system to describe the dynamics of supply chain impact on the environment. Section 4 reports the simulation and performance analysis of the proposed dynamical systems. Section 5 concludes the work and discusses future extensions.

2 Literature review

In recent years, supply chain sustainability has received much attention among industry and academia. Problems and business practices have enabled many researchers to provide deep understanding of underlying phenomena with regard to supply chain sustainability. In the literature, the techniques for modeling and analyzing sustainable supply chain operations can be classified into two categories: operations research (OR), and Simulation.

OR methods and techniques have been widely used in the existing models to explore the implication of environmental concerns on supply chain design and operations (Gunasekaran et al. 2014). Among the OR related work in the literature, some take into account economic impact as a single objective, while others consider the economic, environmental, and social impacts jointly, thus developing multi-objective programs (Oliveira et al. 2014; Radulescu et al. 2014). The following research uses economic impact as a single objective to address issues in supply chain sustainability. Lababidi et al. (2004) models a supply chain in petrochemical company with uncertain economic conditions by optimizing the total costs regarding procurement, production, transportation, inventory, backlog, and lost sales. Huang et al. (2010) presents a mathematical model for strategic planning of bioethanol supply chain systems, aimed at minimizing the cost of biofuel supply chain of over the planning horizon. Chaabane et al. (2012) discuss a framework of sustainable supply chain design with gaseous emissions by a mixed-integer linear program and evaluate the trade-offs between economic and environmental objectives, thus showing that efficient carbon management is helpful in designing sustainable supply chains. Giovanni (2014) introduces reverse revenue sharing contract into the management of close-loop supply chains with the use of green advertising. They find that successful environmental collaboration is only dependent on recycled products' high residual values and point out that previous findings on supply chain contracting do not consider administrative costs, which results in imprecise decision making. Costa et al. (2014) discusses a vegetable crop supply problem subject to ecologically-based production and short life cycle harvested crops. They develop a linear model for crop rotation plan and then propose a stochastic program with recourse to accommodate uncertain demand. On the other hand, Neto et al. (2008) considers conceptual models with the multiple objectives of cost efficiency and environmental performance, and argues the advantages of using multi-objective programming for designing and evaluating sustainable logistics networks. Guillen and Grossmann (2009) creates a bi-criterion stochastic mixed-integer nonlinear program for the design of sustainable chemical supply chains by both maximizing net present value and minimizing environmental impact. Wang et al. (2011) incorporates cost efficiency and environmental concerns into trade-off decisions with regard to supply chain network design by developing a multi-objective optimization model. You et al. (2012) develops a multi-objective mixed-integer linear program to study sustainable supply chain design and planning problems for producing cellulosic ethanol through the consideration of major characteristics such as supply seasonality and geographical diversity, demand distribution, regional economy, government incentives, and so on. Perez et al. (2014) reviews published papers between 1982 and 2014 with regard to sustainable development of urban passenger transport system and discusses the application of multi-criteria decision making techniques to addressing environmental, economic, and social issues.

OR models, however, consider specific scenarios of the supply chains in time instead of dynamic behavior between supply chain operations (Wang and Lei 2012; Wang et al. 2014). Therefore, simulation has been widely used in addressing sustainable concerns in supply chain management because it is insensitive to parameter variations and can capture dynamics of supply chains. Cruz (2008) develops a dynamic framework for the modeling and analysis of supply chain networks with corporate social responsibility through integrated environmental decision-making and provides some qualitative properties of the dynamic trajectories, under suitable assumptions. Byrne et al. (2010) reviews and analyses the use of quantitative analysis for supporting supply chain decision makers in choosing the most environmentally friendly supply chain design, as well as investigate the potential use of discrete event simulation as a method of capturing the dynamic nature of modern supply chain design and operation. Guide and Wassenhove (2006, 2009) studies the design, control, and operation of closed loop supply chain to maximize value creation over the life-cycle of a product, with the dynamic recovery of value from different types and volumes of returns. Duvemo et al. (2014) studies cost-plus-loss problem in forestry planning where they stimulate the continuous planning process of the forest owner at the tactical and operational levels.

Despite simulation's advantages in modeling and analyzing sustainable supply chains, it is unable to model complex dynamic systems and their optimal control problems in an integrative way. In the case of sustainable supply chains, sustainable operations decisions are a function of many key variables, which often strongly interact with one another, thus forming a complex dynamic system. Nonlinear dynamic system is well suited for modelling and managing sustainable supply chains because it is capable of addressing the complexity of dynamic systems in a holistic view and identifies the dynamic mechanism of the interactions between supply chains and environment. While these OR and simulation models provide different perspectives to the research in supply chain sustainability, none of them provides an integrative, comprehensive approach of capturing the dynamics of supply chain impact on the environment.

3 Problem formulation

This section describes techniques for modeling the dynamic impact of supply chain systems on the environment based on product life cycle theory.

The product life cycle consists of four different phases: introduction, growth, maturity, and decline as shown in Fig. 2.

When a product is introduced, the demand for the product is low, but the development and operating costs are very high. In the growth phase, companies start to benefit from a strong growth in sales so that the overall profits increase rapidly. During the maturity stage, companies have established their products and attempt to maintain and maximize the market share they have developed. After maturity, the market size for the product begins to decrease, i.e., decline phase, due to market saturation or because of consumers' switch to other competitors. Therefore, the product demand is dynamic during its life cycle as seen in Fig. 2, which can be described by nonlinear dynamic systems.

3.1 Mathematical model

Supply chains can be seen as biological systems that convert raw materials and/or semi-finished products into finished products. According to product life cycle theory described

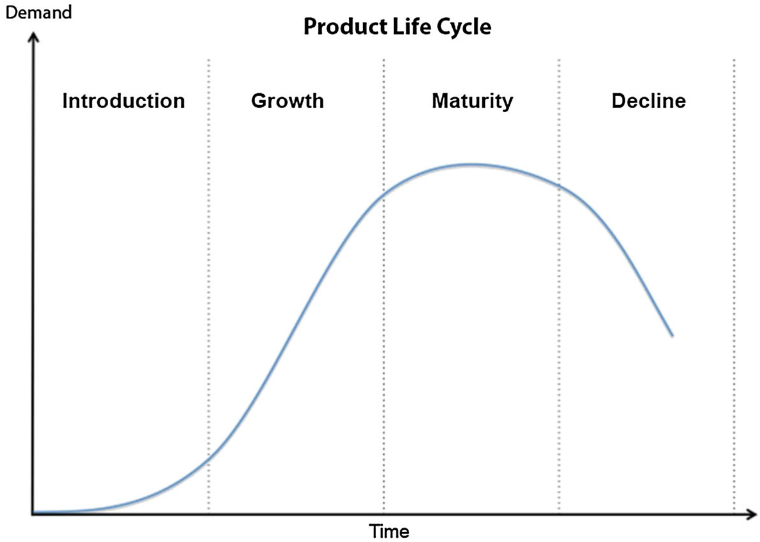

Fig. 2 Product dynamics in the life cycle of a product

above, a model that characterizes the interaction of supply chains with the environment is developed, using the theory of nonlinear dynamic system. During the planning horizon T, supply chains produce $x_1(t)$ units of finished products by using $x_2(t)$ units of resources (i.e., raw materials and/or components), which yields the profit of $x_3(t)$. Resources are supplied at the rate of b and consumed at the rate of a. Since production is affected by the amount of available resources and maximum capacity, K, that environment carries, p_m represents the maximum production rate that supply chain systems are designed to achieve. As a product enters decline phase, it will be recycled for remanufacturing at the rate of m or disposal, which results in the recycling cost denoted by μ. The impact of the entire supply chains on environment is reflected by environment cost per unit, f.

The notations used in this paper are summarized as follows.

$x_1(t)$ = The total number of units of products in a supply chain at time t;
$x_2(t)$ = The total number of units of available resources in a supply chain at time t;
$x_3(t)$ = The profit of a supply chain at time t;
p_m = Design production rate;
d = Demand rate;
m = Remanufacturing rate;
b = Supply rate of resources;
a = Consumption rate of resources;
r = Price of a finished product per unit;
c = Cost of a finished product per unit;
f = Environmental cost per unit;
μ = Cost of recycling end-of-life products;
K = Maximum supply capacity of resources;
T = Planning horizon.

Thus the problem can be formulated as the following nonlinear dynamic system:

$$
(\mathbf{P})\begin{cases}
\frac{dx_1(t)}{dt} = (p(x_2) - d + m)\, x_1(t) & (1)\\
\frac{dx_2(t)}{dt} = bx_2(t)\,(1 - x_2(t)/K) - ax_1(t)\,\frac{x_2(t)}{x_2(t)+K} & (2)\\
\frac{dx_3(t)}{dt} = (r - c)\, x_1(t)\,\frac{x_2(t)}{x_2(t)+K} - fx_2(t) - \mu x_1(t) & (3)\\
x(0) = x_0 & (4)
\end{cases}, \quad t \in [0, T)
$$

where $p(x_2)$ is relevant to p_m, x_2 and K_1, i.e., $p(x_2) = p_m \frac{x_2(t)}{x_2(t)+K}$.

The first equation (1) in (**P**) describes the increase in the amount of products in supply chain system at time t, where $p(x_2)$ represents the effective production rate, expressed in $p_m \frac{x_2(t)}{x_2(t)+K}$, which is related to the amount of available resources in the current environment. As available resources continue to grow, the total amount of products in current system increases in a nonlinear fashion. Since d denotes the demand rate, and m is the remanufacturing rate, $p(x_2) - d + m$ is the actual production rate at time t. The first and second components in (2) formulate the dynamic process of supply and consumption of resources, respectively, where K represents the maximum capacity of resources that the environment can provide to the supply chain system. Equation (3) is used to evaluate the performance of supply chain sustainability through measuring supply chain profitability. The first item in (3) denotes the revenue that sustainable operations generate, while the second and third items describe the environmental costs that supply chain operations and recycling incur, respectively.

3.2 Model analysis

For the convenience of notations, let $x(t) = (x_1(t), x_2(t), x_3(t))$, $f_1(x(t)) = (p(x_2) - d + m)\, x_1(t)$, $f_2(x(t)) = bx_2(t)(K - x_2(t)) - ax_1(t)\frac{x_2(t)}{x_2(t)+K_2}$, $f_3(x(t)) = (r - c)\, x_1(t)\frac{x_2(t)}{x_2(t)+K} - fx_2(t) - \mu x_1(t)$, and $\mathcal{C}$ be the set of all possible solutions to (**P**). To further discuss the system performance, some solution properties of this model are presented below, including the existence, uniqueness and continuity of solutions on initial conditions along with the system's equilibria and stability.

Theorem 3.1 *The solution to* (**P**) *is unique.*

Proof Let $\varepsilon_1 > 0$, $\varepsilon_2 > 0$ and $\varepsilon_3 > 0$ be any real valued numbers, and it follows, for any $x(t)$ and $y(t)$ in $\mathcal{C}$,

$$
\begin{aligned}
|f_1(x) - f_1(y)| &\le \varepsilon_1 \,||x - y||\\
|f_2(x) - f_2(y)| &\le \varepsilon_2 \,||x - y||\\
|f_3(x) - f_3(y)| &\le \varepsilon_3 \,||x - y||
\end{aligned}
$$

Thus, f_1, f_2 and f_3 are all Lipchitz continuous, leading to the completion of this proof. □

Theorem 3.2 *The solution to* (**P**) *is continuous with respect to the initial value,* x_0.

Proof According to Theorem 3.1, for any given $x_0 \in \mathcal{C}$ and $y_0 \in \mathcal{C}$, a solution to (**P**) exists. Since f_1, f_2 and f_3 are Lipchitz continuous, it follows that for any $x(t)$ and $y(t)$ in $\mathcal{C}$ and for any $\varepsilon > 0$

$$||x - y|| \le \| x_0 - y_0 \| \le \varepsilon,$$

which completes the proof. □

In general, small perturbations of initial conditions can result in considerable variations on the solutions to dynamic systems. The stability analysis is performed to determine whether the dynamic behavior of supply chain impact on the environment is stable. Consider the dynamic system defined by equations (1) and (2), which formulate the dynamics of supply chain and environment, respectively, and we will discuss the stability of the system, denoted by (**DP**), in terms of its equilibria.

Theorem 3.3 **(DP)** *has two equilibria as follows:*

(a) For supply chain dynamics, i.e., Eq. (1), $x_2^* = \frac{p_{\mathrm{m}}-d+m}{d-m}$, $(d > m)$;

(b) For environment dynamics, i.e., Eq. (2), $x_1^* = \left(-\frac{b}{aK}\right)\left[\left(x_2 - \frac{K-K_2}{2}\right)^2 - \left(\frac{K+K_2}{2}\right)^2\right]$.

Proof According to the definition of equilibrium, it follows that $\frac{dx_1(t)}{dt} = 0$ and $\frac{dx_2(t)}{dt} = 0$.

(a) Since $\frac{dx_1(t)}{dt} = 0$, it follows that $(p(x_2) - d + m)\, x_1(t) = 0$ and further $p(x_2) = d-m$. Thus we may solve for x_2 and obtain the first equilibrium for (**DP**): $x_2^* = \frac{p_m-d+m}{d-m}$, where we assume $d > m$ because in practice the demand rate of the product is greater than its remanufacturing rate.

(b) It follows from $\frac{dx_2(t)}{dt} = 0$ that $bx_2(t)(1 - x_2(t)/K) - ax_1(t)\frac{x_2(t)}{x_2(t)+K_2} = 0$, which is equivalent to the following: $bx_2(t)(1 - x_2(t)/K) = ax_1(t)\frac{x_2(t)}{x_2(t)+K_2}$. Expanding and reorganizing, we obtain the second equilibrium: $x_1^* = \left(-\frac{b}{aK}\right)\left[\left(x_2 - \frac{K-K_2}{2}\right)^2 - \left(\frac{K+K_2}{2}\right)^2\right]$.

□

Theorem 3.4 *The dynamics of* **(DP)** *is stable.*

Proof To prove that the dynamics of (**DP**) is stable, it is sufficient to show that the trace of Jacobian matrix of f_1 and $f_2$is negative and its determinant is positive. We will complete the stability proof in two phases: a) showing that the trace of Jacobian matrix, $\frac{\partial f_1}{\partial x_1} + \frac{\partial f_2}{\partial x_2}$, is negative; and b) demonstrating that its determinant is positive.

(a) Let us start with the first phase, compute the Jacobian matrix with equilibria, and determine the sum of $\frac{\partial f_1}{\partial x_1}$ and $\frac{\partial f_2}{\partial x_2}$ as follows:

$$J\left(x_1^*, x_2^*\right) = \begin{pmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} \end{pmatrix} = \begin{pmatrix} p\left(x_2^*\right) - d + m & p_m K_1 \frac{x_1^*}{(K_1+x_2^*)^2} \\ (-a)\frac{x_2^*}{x_2^*+K_2} & b\left(1 - \frac{2x_2}{K}\right) - ax_1^* \frac{K_2}{(K_2+x_2^*)^2} \end{pmatrix},$$

$$\begin{aligned} \frac{\partial f_1}{\partial x_1} &= p\left(x_2^*\right) - d + m \\ &= \frac{\left[(p_m - d + m) + \sqrt{K_1}(d-m)\right]\left[(p_m - d + m) - \sqrt{K_1}(d-m)\right]}{(d-m)K_1 + (p_m - d + m)}. \end{aligned}$$

Since $(p_m - d + m) + \sqrt{K_1}\,(d - m) > 0$, $(d - m)\,K_1 + (p_m - d + m) > 0$ and $(p_m - d + m) - \sqrt{K_1}\,(d - m) < 0$, it follows that $\frac{\partial f_1}{\partial x_1} < 0$.

$$\frac{\partial f_2}{\partial x_2} = b\left(1 - \frac{2x_2^*}{K}\right)$$

$$-ax_1^*\frac{K_2}{\left(K_2 + x_2^*\right)^2} = \left(\frac{b}{K}\right)\left[\left(K - 2x_2^*\right) - K_2\frac{-\left(x_2^* - \frac{K-K_2}{2}\right)^2 + \left(\frac{K+K_2}{2}\right)^2}{\left(K_2 + x_2^*\right)^2}\right].$$

Let $g\left(x_2^*\right) = \left(K - 2x_2^*\right)\left(K_2 + x_2^*\right)^2$ and $h\left(x_2^*\right) = K_2\left[-\left(x_2^* - \frac{K-K_2}{2}\right)^2 + \left(\frac{K+K_2}{2}\right)^2\right]$, then $\frac{\partial f_2}{\partial x_2}$ can be expressed in terms of $g\,(x)$ and $h\,(x)$ as follows.

$$\begin{aligned}\frac{\partial f_2}{\partial x_2} &= \left(\frac{b}{K}\right)\frac{\left(K - 2x_2^*\right)\left(K_2 + x_2^*\right)^2 - K_2\left[-\left(x_2^* - \frac{K-K_2}{2}\right)^2 + \left(\frac{K+K_2}{2}\right)^2\right]}{\left(K_2 + x_2^*\right)^2}\\ &= \left(\frac{b}{K\left(K_2 + x_2^*\right)^2}\right)\left(g\left(x_2^*\right) - h\left(x_2^*\right)\right).\end{aligned}$$

In order that $\frac{\partial f_2}{\partial x_2} \le 0$, we only need to prove that $g\left(x_2^*\right) \le h\left(x_2^*\right)$ for any $x_2^* \ge 0$. Since $\frac{dg\left(x_2^*\right)}{dx} = (-4)\left(K_2 + x_2^*\right) < 0$ and thus $g\,(x)$ is strictly decreasing, it follows that $g\,(0) = KK_2 \ge g\left(x_2^*\right)$. On the other hand, following $h\,(0) = KK_2$, we can infer that $g\left(x_2^*\right) \le h\left(x_2^*\right)$ and thus $\frac{\partial f_2}{\partial x_2} \le 0$.

(b) Now let us show that the determinant of $J\left(x_1^*, x_2^*\right)$ is positive.

$$\det\,(J) = \frac{\partial f_1}{\partial x_1}\frac{\partial f_2}{\partial x_2} - \frac{\partial f_1}{\partial x_2}\frac{\partial f_2}{\partial x_1} = \frac{\partial f_1}{\partial x_1}\frac{\partial f_2}{\partial x_2} + \left(\frac{ax_2^*}{x_2^* + K_2}\right)\left[p_m K_1\frac{x_1^*}{\left(K_1 + x_2^*\right)^2}\right].$$

It follows from the proof in a) that $\frac{\partial f_1}{\partial x_1}\frac{\partial f_2}{\partial x_2} \ge 0$, and hence we have that $det\,(J) \ge 0$, which completes the proof. □

The theorem with regard to system stability implies that the solutions do not change considerably under small perturbations. In other words, the proposed model is robust and well describes the interaction of supply chains on the environment, so it can be used for further analysis.

4 Performance analysis

More and more companies have realized the importance of sustainable supply chains not only because of inherent environmental and social risks, but also due to many rewards supply chain sustainability can deliver. This section discusses the impact of environmental cost, design production rate, and demand on the supply chain systems to better understand the dynamics of sustainable supply chains, predict the future behavior of the system, and ultimately identify and evaluate supply chain strategies capable of minimizing inefficiencies in sustainable supply chains.

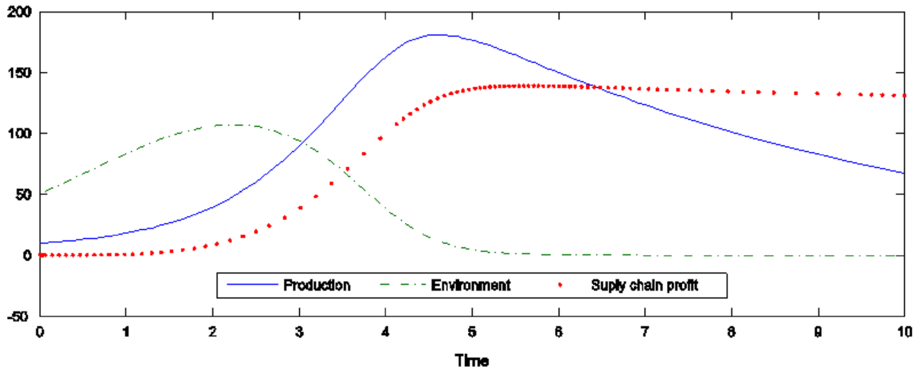

Fig. 3 Dynamics of production, environment, and supply chain profitability

4.1 Dynamics simulation

Compared with the product life cycle shown in Fig. 2, this section attempts to simulate the interaction between environment and supply chains. The setting of the parameters used in this simulation is below:

- $p_m = 2$; $d = 0.4$; $m = 0.2$; $b = 1$; $a = 2$; $r = 3$; $c = 2$; $f = 0.1$; $\mu = 0.01$; $K = 200$; $K_1 = 100$; $K_2 = 100$; $K_3 = 50$; $T = 10$.
- Initial values: $x_1(0) = 10$, $x_2(0) = 50$, $x_3(0) = 0$.

Figure 3 is concerning the simulation results with the set of the above parameter values, where solid line denotes the dynamics of production, dashed line represents the environmental dynamics, and dotted line illustrates the variations of supply chain profitability over time. In the introduction phase of a new product, although sufficient resources are available, the amount of the product in the supply chain system is small, so supply chain profit is negative. As the sales of new product grow and more resources are consumed, supply chain profit increases accordingly. At the maturity phase of its life cycle, the resource supply reaches the maximum capacity. Afterwards, the decline on the sales and the reduction of available resources lead to the decrease of supply chain profit, which is in accordance with product life cycle theory.

Figure 4 exhibits the impact of production on the environment and supply chain profitability, respectively. With the parameter values given in Sect. 4.1, it can be seen that the amount of product in the supply chain system reaches its maximum limit of 190 during its maturity phase and then starts decreasing. This is mainly because of the limitation on the maximum supply capacity of resources. On the other hand, since the amount of product declines after maturity, the consumption of resources diminishes, but the environmental impact of end-of-life products increases.

The following Fig. 5 reveals the impact of the environment on production and supply chain profitability, respectively. The increase in resource consumption ensures that sufficient products are produced to satisfy growing demand. Once the environment approaches its maximum supply capacity, the negative impact of the environment on supply chains appears (e.g., supply shortages), thus resulting in sales decline, which is consistent with the figure to the right of Fig. 5. Figures 4 and 5 together imply that the interaction between production and the environment reflects the respective dynamics of production and the environment, and their interrelationship is complex. Moreover, they tell us that supply chain sustainability

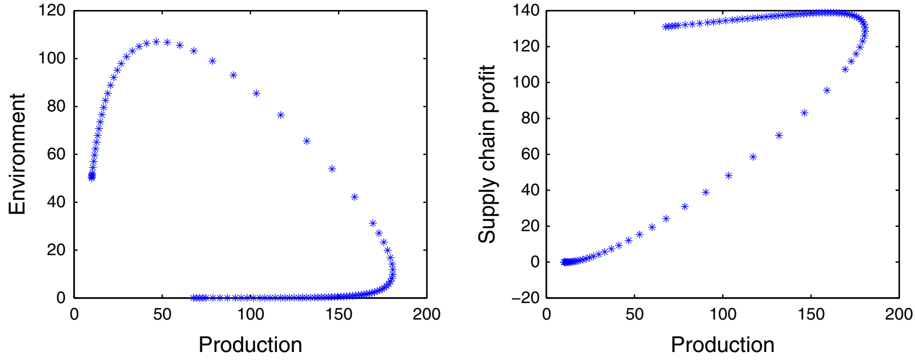

Fig. 4 Impacts of production on environment and supply chain profitability

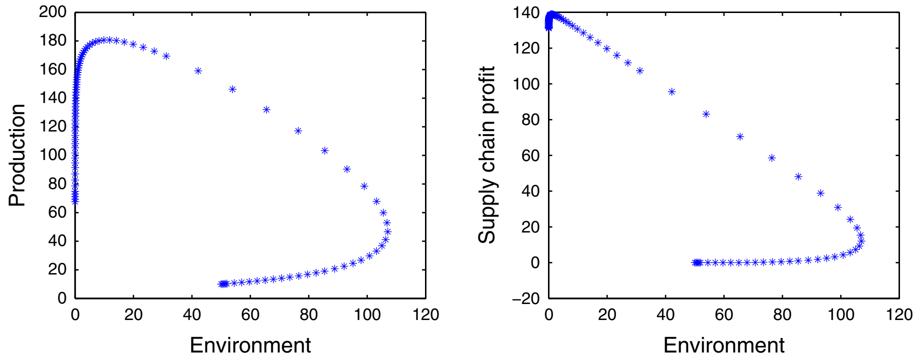

Fig. 5 Impacts of environment on production and supply chain profitability

is an organization's competitive advantage, and can improve efficiency and supply chain profitability over the long term, as it shows the firm's ability to mitigate, respond to, and recover from potential global risks.

4.2 The impact of environment cost on supply chain profit

Because of negligent environmental regulations, significant price pressures, and abundant natural resources, supply chain systems have severe environmental impact, which includes water pollution, toxic waste, long-term damage to ecosystems, hazardous air emissions, and deforestation as well as high greenhouse gas emissions and energy use. In this dynamic model, the impact of supply chain on the environment is represented by the environmental cost f. Hence, the impact of the environment on supply chain profit is studied as shown in Fig. 6.

In Fig. 6, when the environment cost, f, is 0.1, the supply chain profit remains positive and grows at the lowest rate over time. However, the increase from 0.3 to 0.5 in environmental costs f results in supply chain loss initially and then yields rapid growth in supply chain profit. This indicates that in the introduction phase of new products, supply chain operations consume more resources and have more significant impact on the envi-

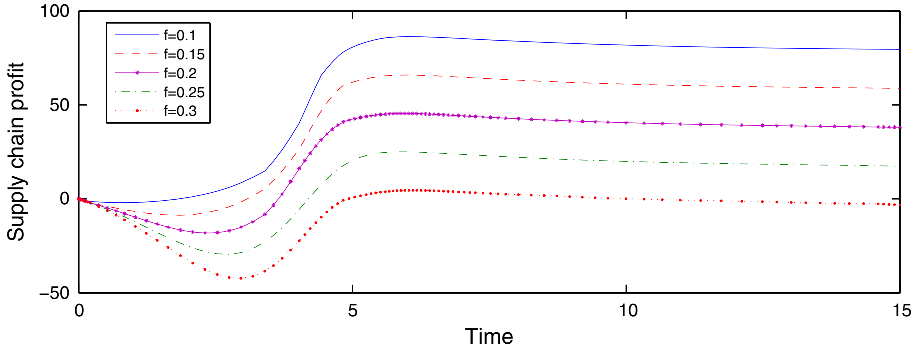

Fig. 6 Impact of environmental costs on supply chain profit

ronment, but supply chain systems do not produce profits. After new products enter the growth phase, supply chain systems interact with environment significantly such that supply chain profitability is improved. On average, the total supply chain profit over the planning horizon is decreased since more resources are used and environmental impact is more significant.

While organizations seek supply chain profit and cost reductions, they should focus more on the eco-friendly design of products, services, and supply chain systems, as well as the sustainable production, inventory and distribution operations. This is because sustainable supply chain management can be a strong driver of value and success for organizations and society. For instance, companies developing sustainable products or services have added new features and performance to existing products and even generated new products. Sustainable products may result in fewer negative environmental impacts than traditional products or have improved end-of-life collection and disposal options. It is also possible for the sustainability of products to be a differentiating factor and to lead to increased sales.

4.3 The impact of design production capacity on dynamics

As an important function in supply chains, production affects supply chain sustainability significantly. Figure 7 presents the impact of design production rate, p_m, on sustainable supply chain dynamics over time.

As p_m becomes bigger, resources are consumed rapidly, and product enters maturity quickly, while supply chain profit declines. This is true in practice because high production rate means a large amount of products produced in the supply chain system, but with limited available resources, supply chain systems turn into steady state rapidly. Meanwhile, the rise in production rate results in high environmental costs, which decreases supply chain profit. However, the presence of remanufacturing rate, m, counteracts growing production rate, thus reducing environmental impact of supply chains. Therefore, organizations should focus on remanufacturing rather than simply production operations because remanufacturing not only serves strategic interests for companies, but also provides considerable benefits for the forward progress of sustainable supply chains. According to APIC Foundation's survey, 68 % of respondents felt that sustainability was primary advantage with remanufacturing, and 41 % already considered it a formal component of their organizations' sustainability policies.

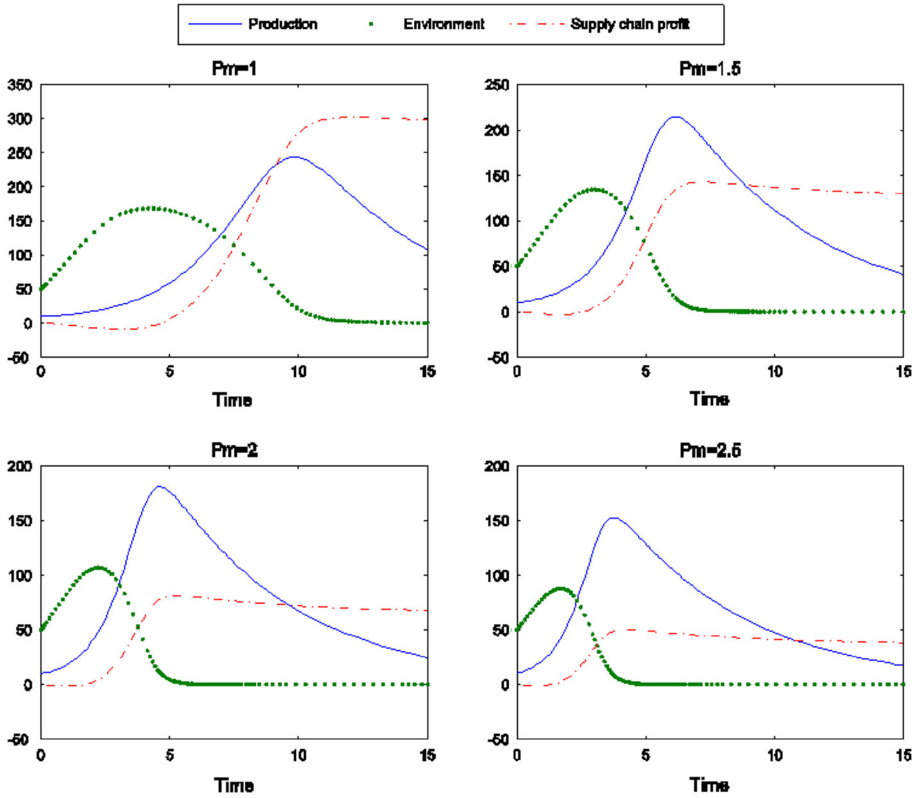

Fig. 7 Impact of designed production capacity on the dynamics of sustainable supply chains

Remanufacturing is key to supply chain growth and drives supply chain sustainability (APICs Foundation 2013).

4.4 The impact of demand rate on dynamics

Demand plays an extremely important role in supply chain management as it brings in revenues. This section contains the analysis with respect to how the variations in demand rate impact the interaction between the environment and supply chains.

In Fig. 8, as demand rate increases from 0.1 to 0.25, the amount of products in supply chain systems decreases quickly, and supply chain profitability rises accordingly. It can be inferred from the impact of demand rate on sustainable supply chain dynamics that the production of more products to meet the increasing demands has the significant impact on the environment because supply chains interact with the environment more frequently. Hence forecasting demand accurately is essential to effectively managing sustainable operations as it helps avoid the impact of excess production and inventory on the environment as well as enables decision makers to focus more on supply chain sustainability. Nevertheless, it is difficult in practice to precisely predict the demand due to the dynamics of market (i.e., price) and supply chain (i.e., bullwhip effect), so an effective modelling and analytic tool for supply chain sustainability is indispensable.

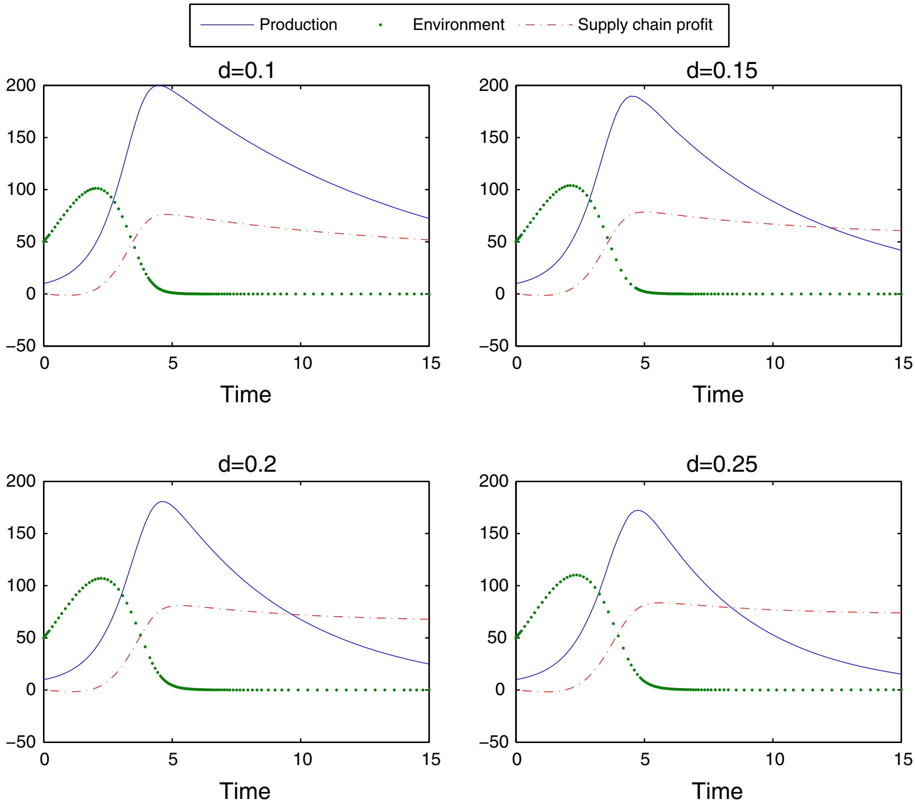

Fig. 8 Impact of demand rate on the dynamics of sustainable supply chains

5 Conclusion and future extensions

This paper has explicitly studied the dynamic impact of supply chain operations on environment, which was motivated by the supply chain practices in apparel industry. The focus of this work is on the development and simulation of nonlinear dynamic system capturing the dynamics of environmental impact of supply chains, which provides new direction of modeling sustainable supply chains and reveals the nonlinear dynamic nature of complex supply chains. Furthermore, this dynamic system can serve as the foundation for future extensions such as modeling sustainable supply chains with market dynamics or supply chain disruptions. Lastly, this paper illustrates the dynamic impact of supply chains on the environment explicitly instead of implicitly as in the models described by either OR or system dynamics.

A mathematical model describing the interaction between supply chains and environment has been developed, using the techniques for modeling complex dynamic nonlinear systems. In addition to the discussion on solution properties as well as on the system's equilibrium and stability, system simulation has been performed to validate the proposed dynamic systems according to three different parameters, i.e., design production capacity, environmental cost, and demand rate. The results showed the dynamic relationship between the environment and supply chain systems. This provides useful insight into how much impact the variations on production, environment, and demand would have on the dynamics and economic performance of sustainable supply chain systems. In particular, the relation between the environment and supply chain profitability indicates that small increase in environment cost can cause significant decrease in supply chain profitability. In other words, it is shown that supply chain sustainability is essential to the continuous improvements of supply chain performance.

Since supply chain sustainability is to manage the environmental, economic, and social impacts, the nonlinear dynamic system proposed in this paper is only concerned with economic and environmental impacts of supply chain systems without taking into account the social impact. Hence, social measure on supply chain sustainability should be incorporated into the development of the system to achieve the overall measurement on the sustainable supply chain performance. In addition, the analysis and simulation on the proposed system are both based on the given set of model parameters, which may be easily affected by variations in the environment and supply chain systems. Parameter identification should be provided to find a set of optimal model parameters with which the proposed system can best describe the dynamics of supply chain impact on the environment. Furthermore, deterministic simulation on the proposed system in this paper should be extended to the stochastic simulation.

This paper is of interest to both researchers and practitioners. On one hand, this paper provides an underlying framework for further research on parameter identification, sensitivity analysis, and even the design of its optimal control system, which leads to a better understanding of environmental impact of supply chain operations. As the interaction of supply chains with the environment is illustrated by explicit nonlinear dynamic systems, on the other hand, this paper can help firms determine critical factors affecting supply chain sustainability, and develop decision making tools for evaluating and measuring the performance of sustainable supply chains.

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References

Agbonkhese, S. E. (2010). Measuring environmental and social sustainability in the apparel supply chain. MIT. http://dspace.mit.edu/bitstream/handle/1721.1/60831/697300418.pdf. Accessed 5 Oct 2014.

APICs Foundation. (2013). Sustainable supply chains: Making value the priority. Pwc. http://www.apics.org/docs/default-source/careers-development/final_pwcwhitepaper_web.pdf?sfvrsn=4. Last access on 14 Aug 2014.

Byrne, P. J., Heavey, C., Ryan, P., & Liston, P. (2010). Sustainable supply chain design: Capturing dynamic input factors. *Journal of Simulation*, *4*(4), 213–221.

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.

Costa, A. M., Santos, L. M., Alem, D. J., & Santos, R. (2014). Sustainable vegetable crop supply problem with perishable stocks. *Annuals of Operations Research*, *1*(219), 265–283.

Cruz, J. M. (2008). Dynamics of supply chain networks with corporate social responsibility through integrated environmental decision-making. *European Journal of Operational Research*, *3*(184), 1005–1031.

Duvemo, K., Lamas, T., Eriksson, L. O., & Wikstrom, P. (2014). Introducing cost-plus-loss analysis into a hierarchical forestry planning environment. *Annuals of Operations Research*, *1*(219), 451–431.

Giovanni, P. D. (2014). Environmental collaboration in a closed-loop supply chain with a reverse revenue sharing contract. *Annuals of Operations Research*, *1*(220), 135–157.

Guide, V. D. R, Jr, & van Wassenhove, L. N. (2006). Closed-loop supply chains: An introduction to the feature issue (part 1). *Production and Operation Management*, *15*(3), 345–350.

Guide, V. D. R, Jr, & van Wassenhove, L. N. (2009). The evolutions of closed loop supply chain research. *Operations Research*, *57*(1), 10–18.

Gunasekaran, A., Irani, Z., & Papadopoulos, T. (2014). Modeling and analysis of sustainable operations management: Certain investigations for research and applications. *Journal of Operational Research Society*, *6*(65), 806–823.

Guillen, G., & Grossmann, I. (2009). Optimal design and planning of sustainable chemical supply chains under uncertainty. *Process Systems Engineering*, *55*(1), 99–121.

Huang, Y., Chen, C., & Fan, Y. (2010). Multistage optimization of the supply chains of biofuels. *Transportation Research Part E: Logistics and Transportation Review*, *46*(6), 820–830.

Lababidi, H., Ahmed, M., Alatiqi, I., & Al-Enzi, A. (2004). Optimizing the supply chain of a petrochemical company under uncertain operating and economic conditions. *Industrial Engineering and Chemical Research*, *43*(1), 63–73.

Linton, J. D., Klassen, R., & Jayaraman, V. (2007). Sustainable supply chains: An introduction. *Journal of Operations Management*, *25*(6), 1075–1082.

Neto, J., Ruwaard, J. M., Nunen, J., & Heck, E. (2008). Designing and evaluating sustainable logistics networks. *International Journal of Production Economics*, *11*(2), 195–208.

Oliveira, C., Coelho, D., & Antunes, H. (2014). Coupling input–output analysis with multiobjective linear programming models for the study of economy-energy-environment-social (E3S) trade-offs: A review. *Annals of Operations Research*. doi:10.1007/s10479-014-1773-5.

Perez, J. C., Carrillo, M. H., & Montoya, J. R. (2014). Multi-criteria approaches for urban passenger transport systems: A literature review. *Annuals of Operations Research*. doi:10.1007/s10479-014-1681-8.

Radulescu, M., Radulescu, C. Z., & Zbaganu, G. (2014). A portfolio theory approach to crop planning under environmental constraints. *Annals of Operations Research*, *219*(1), 243–264.

Rourke, D. (2014). The science of sustainable supply chains. *Science*, *344*, 1124–1127.

United Nations Global Compact. (2014). Supply chain sustainability: A practical guide for continuous improvement. *6*(25), 1075–1082.

Wang, G., Feng, E., & Xiu, Z. (2007). Vector measure for explicit nonlinear impulsive system of glycerol bioconversion in fed-batch cultures and its parameter identification. *Applied Mathematics and Computation*, *2*(188), 1151–1160.

Wang, G., Feng, E., & Xiu, Z. (2008). Modeling and parameter identification of nonlinear impulsive dynamical system. *Journal of Process Control*, *18*(5), 458–464.

Wang, G., Feng, E., & Xiu, Z. (2009). Vector measure as controls for explicit nonlinear impulsive dynamical system. *Journal of Mathematical Analysis and Applications*, *1*(351), 120–127.

Wang, F., Lai, X., & Shi, N. (2011). A multi-objective optimization for green supply chain network design. *Decision Support Systems*, *51*(2), 262–269.

Wang, G., & Lei, L. (2012). Polynomial-time solvable cases of the capacitated multi-echelon shipping network scheduling problem with delivery deadlines. *International Journal of Production Economics*, *137*(2), 263–271.

Wang, G., Lei, L. & Lee, K. (2014). Supply chain scheduling with receiving deadlines and a non-linear penalty. *Journal of Operational Research Society* (advance online publication 19 February). doi:10.1057/jors.2014.2.

You, F., Tao, L., Graziano, D., & Snyde, S. (2012). Optimal design of sustainable cellulosic biofuel supply chains: Multi-objective optimization coupled with life cycle assessment and input-output analysis. *Process System Engineering*, *58*(4), 1157–1180.