Fuzzy input–output model for optimizing eco-industrial supply chains under water footprint constraints

Kathleen B. Aviso, Raymond R. Tan, Alvin B. Culaba, Jose B. Cruz Jr

1. Introduction

The impact of human activities on the environment is now a global concern, and in particular, climate change is perceived to be the most significant problem facing the world today. It is expected to affect global freshwater resources as precipitation patterns change, glaciers melt and sea levels rise. These effects will further intensify water stress experienced from continued population growth, economic development and industrial pollution (Rockstrom et al., 2009). It has been suggested that water may be the limiting resource for some economic activities. Although the industrial sector takes up only an average 22% of the water being used globally, water usage intensity is significant to all businesses whose sustainability will depend on its availability, cost and quality (WBCSD, 2006). Furthermore, industries utilize raw materials derived from agriculture, which utilizes 70% of the global water consumption. This is particularly true in producing biofuels, which have gained popularity due to both energy security and climate change issues. It has been argued that large-scale production of biofuels may be constrained by the availability of agricultural land (Ponton, 2009; Nonhebel, 2005) and water resources (Gerbens-Leenes et al., 2009; Tan et al., 2009a,c; Yang et al., 2009; Harto et al., 2010). The link between industrial and agricultural activity indicates that the total water intensity (or water footprint) of an organization or region is not only limited to the operational water directly utilized in processing the final product, but also includes the water utilized in all processes involved in the product supply chain. Accounting for the direct and indirect water use in industrial systems leads to transboundary concerns of virtual water trade vis-à-vis local water availability. For industries, the increasing value of freshwater resources can be viewed as an opportunity for creating new businesses which will provide solutions towards improving the sustainability of industrial water utilization (WBCSD, 2006).

Recent trends in waste management and environmental protection have focused on the development of cleaner production strategies which promote reduction in the generation of waste by reducing the consumption of resources. One approach is industrial ecology (IE), which adopts mechanisms found in natural ecosystems and applies them to industrial systems (Frosch and Gallopoulos, 1989). In particular, industrial symbiosis (IS) where waste materials of one industry are utilized as inputs for another industry can lead to synergies which yield greater benefits than can be achieved by companies acting independently. According to Chertow (2007) the exchange of common utilities such as energy...
and water often becomes a precursor to the emergence of full blown IS, which may eventually include exchanges of highly specific raw materials. Process systems engineering approaches have recently been developed to aid in the design of IS schemes. For example, Spriggs et al. (2004) and Foo (2008) used pinch analysis for identifying targets for establishing water exchange networks, while Liao et al. (2007) and Lovelady and El-Halwagi (2009) used mathematical programming for designing water exchange networks between different plants in an eco-industrial park (EIP). Chew et al. (2008) utilized the concept of a centralized hub topology for collecting and redistributing water, while Lovelady et al. (2009) used a modified property-based approach for designing EIP networks. Furthermore, as the establishment of these networks requires the cooperation of the participating plants, game theoretic approaches have been used to incorporate the potentially conflicting interests of the participants in designing the network. Kim and Lee (2007) utilized the concept of benefit sharing for designing Pareto optimal networks, and Lou et al. (2004) used energy-based game theoretic analysis for assessing economic and environmental sustainability strategies under data uncertainty. Chew et al. (2005, in press) used game theory approach to assess payoffs based on different water network designs. More recently, Aviso et al. (2010a, b) used fuzzy optimization to integrate goals set by the participants in designing the network and took into account the role of the EIP authority in facilitating the emergence of IS through economic incentives or disincentives. Fuzzy sets have been used in decision-making to account for uncertainties and inconsistencies in goals, objectives and constraints (Bellman and Zadeh, 1970). Its use in optimizing the design of IS schemes has the advantage of representing and integrating the multiple objectives arising from the presence of multiple decision-makers into a single parameter within the model. Fuzzy sets have also been used for other environmental applications, such as the evaluation of the sustainability of production processes (Tseng et al., 2008, 2009a,b), the development of a municipal solid waste management model (Tseng and Lin, 2009) and the selection of sustainable industrial areas (Fernández and Ruiz, 2009) where evaluation criteria were characterized with uncertainty. Recent applications of fuzzy concepts in life cycle based optimization models have also been reported (Tan, 2008; Tan et al., 2008, 2009c).

However, most current studies on the design of water exchange networks have thus far not considered water consumed by a company along its supply chain. In order to assess the actual water intensity of products and processes, the concepts of virtual (Allan, 1998; Chapagain and Orr, 2009) and water footprint (Hoekstra and Hung, 2002; Chapagain and Hoekstra, 2004) have been introduced. These were initially utilized to analyze the water footprint and virtual water trade of nations due to the consumption of agricultural based products (Chapagain et al., 2006; Chapagain and Hoekstra, 2007; Velazquez, 2007) and have been recently extended to the product brand level (Ridoutt et al., 2009; Ridoutt and Pfister, 2010). The relationship of the water footprint to life cycle assessment and similar concepts has been discussed by De Benedetto and Klemes (2009). The concept of water footprint is utilized to assess water intensity at various levels of economic activity depending on the scope and goal of the study being undertaken. The main building blocks are the processes being accounted for either throughout a supply chain or as bounded by the region of interest. The total water footprint is defined as the associated amount of freshwater used (directly and indirectly) to run the business unit; it consists of operational water directly used by the plants, and the indirect water embedded in the raw materials utilized by the plant in the form of virtual water (Gerbens-Leenes and Hoekstra, 2008). The business water footprint is the total amount of water utilized in the supply chain of a business unit in order to support its activities and can be considered as a consumption-based indicator for water use. On the other hand, the water footprint may also be defined to account for the water intensity associated with all the activities within a specified geographical region (Hoekstra et al., 2009) and thus reflects a production-based indicator of water use. The total water footprint consists of three components, namely, green water, blue water and gray water. Green water pertains to the amount of rainwater evaporated or rainwater incorporated in the product during the production process and is typically applicable to agricultural products. It accounts for the rainwater required to grow a crop and its resulting product yield (Hoekstra et al., 2009). These values are typically derived from models such as the CROPWAT (FAO, 2009). Blue water is the amount of surface and ground water evaporated or incorporated into the product due to the production process or service and is equivalent to the amount of surface or ground water utilized which does not return to the environment. If water is taken up in a process and not returned to the environment in liquid form, the net consumption is zero, and all that is required is a footprint index that takes into account the degradation of water quality. This gray water footprint component refers to “the volume of water required to dilute pollutants to such an extent that concentrations are reduced to agreed maximum acceptable levels” (Hoekstra and Chapagain, 2007). It is simply a quantitative index of the extent of harm the pollution in the wastewater stream will contribute, and does not necessarily imply deliberate dilution of wastewater from plant operations. A greater value of gray water indicates that the pollution load of the wastewater stream is high. Furthermore, it takes into consideration the assimilative capacity of the receiving body of water. The overall water footprint is simply the sum of these components. In the production of cotton textile for example, growing the crop requires water. This water requirement will consist of green and blue water footprints. Suppose, for example, that 2000 tons of rainwater (green water) and 5000 tons of irrigation water (blue water) are required to grow a ton of cotton. Furthermore, in order to process the cotton crop into textile, 1000 tons of water is taken up from the environment, and returned as wastewater that meets legislated effluent standards; hence, the associated gray water is 1000 tons. The total water footprint for the production of 1 ton of cotton textile is thus 8000 (2000 + 5000 + 1000) tons.

This paper focuses on developing a model for optimizing the supply chain in the presence of multiple stakeholders/decision-makers and water footprint constraints. The paper is organized as follows. Sections 2 and 3 provide a brief description of the overall nature of the problem being addressed in this paper. Section 4 then discusses the development of the generic model for optimization based on input—output analysis. Two cases are then presented in the succeeding sections to demonstrate the applicability of modified variants of the general model. The first case study accounts water intensity based on the consumer’s perspective and takes into consideration processes which are related vertically via the product supply chain. It optimizes the supply chain network in consideration of water footprint limits set by multiple consumers in the presence of product/process alternatives. The second case study on the other hand utilizes the water footprint concept from a producer’s perspective and accounts for water intensity related to activities contained within a region. It optimizes the exchange network between producers and consumers by satisfying product demands in the presence of resource constraints identified by multiple producers. Finally, conclusions and possible extensions to the problem are presented in the last section.
2. Generic input–output model

The relationship which exists between the production of goods and exchange of materials between economic sectors within a region can be represented by an input–output model (Leontief, 1936, 1951). This basic model has been extended to integrate environmental burdens associated with the consumption of materials in single- and multi-regional trade. It has been utilized as well to assess production flows and evaluate environmental burdens along supply chains (Albino et al., 2002; Albino and Kuhtz, 2004; Kuhtz et al., 2010) or throughout the life cycle of products and processes (Heijungs and Suh, 2002; Suh and Huppes, 2005; Hendrickson et al., 2006).

The basic model is given by Equation (1) which describes the energy and material balance of input and output flows for processes in the system to achieve the desired product outows. Matrix A relates the input and output flows in individual processes. It is assumed that the ratio between energy and material flows within a process is fixed and that these processes may be scaled in order to produce the desired net output of products for the system. Column vector f is the set of final product output flows, and it is referred to as the final output vector. Column vector s on the other hand is the set of proportions specifying the extent to which processes must be scaled in order to satisfy internal demands of processes as well as the desired net outputs.

$$A = f$$  \hspace{2cm} (1)

Note that when A is square and not singular, Equation (1) may be solved to yield a unique solution. On the other hand, when there are excess degrees of freedom, optimization may be done provided that a suitable objective function can be specified. Furthermore, interactions of the system with the environment, which include the consumption of natural resources or the generation of waste, may be analyzed using Equation (2). The environmental flows of the processes associated with Equation (1) and the set of proportions are subjected to a constraint through an intervention matrix B and the total environmental flows given in the inventory vector g as indicated in Equation (2).

$$Bs = g$$  \hspace{2cm} (2)

Recently, Tan et al. (2008; 2009c) utilized the input–output model to develop a fuzzy linear model for the design and optimization of life cycle systems in consideration of fuzzy environmental flow targets and multiple technological alternatives within a single region. Furthermore, it is based on the concept of seeking a “confluence” of fuzzy goals and constraints in a complex decision-making problem (Bellman and Zadeh, 1970), which was later integrated into fuzzy mathematical programming using max–min aggregation (Zimmermann, 1978).

The model of Tan et al. (2008; 2009c) is extended in this paper to the case of multi-region systems that takes into account trade effects which have been integrated in standard IOA models (Wiedmann, 2009). The objective is to optimize the exchange networks between processes or industries related vertically via the product supply chain in the presence of environmental goals, resource constraints and product demands defined by the network participants. The optimization requires the satisfaction of multiple, and potentially conflicting, goals arising from the involvement of several decision-makers. The fuzzy input–output based model developed here is thus able to account for the individual interests of the network participants.

3. Problem statement

The total water footprint of a business unit, an industrial plant or an entire geographic region pertains to the total water consumed in order to sustain its activities. This includes the water used for operations and the water used for the production of raw materials required by the plant. Since raw materials may be acquired from another country or region, environmental burdens may occur in a different location from where the final product is consumed. The general system being considered has \(N_R\) regions, \(N_I\) economic flows (i.e., raw materials, intermediates or products) and \(N_P\) plants or processes which generate the required economic flows. Furthermore, in the production of raw materials and products, there are associated \(N_E\) environmental flows which correspond to relevant environmental footprints (in this work, the model is limited in scope to water footprint components). It is possible to exchange products/by-products among different plants contained in different regions. A product manufactured by one plant serves as raw material for another plant, such that the plants form exchange networks or a supply chain. The requirement of a region for particular products/by-products may be satisfied by producing the product locally if the region has the capacity to do so, or by importing from another region. The production of each product/by-product has associated environmental burdens, and the challenge is how to optimally allocate the environmental burdens between the entities in the network and relate these to water footprint goals and water resource constraints. Water footprint goals may then be set to improve the environmental performance of a business unit throughout its supply chain. On the other hand, water resource availability in a region can limit the production of certain goods in that region. It is therefore important to identify the optimal supply network between several entities in the presence of such water resource constraints or water footprint goals.

4. Mathematical model

The production of goods has associated water footprint. However, products are traded between different regions and environmental consequences associated to a region’s activities may impact the local environment of another (e.g., through virtual water import or export). For example, regions where water is scarce will benefit from importing water-intensive goods from places where water is abundant. The total water footprint of any Region \(k\) may be defined based on a consumer’s or producer’s perspective. The total consumption-based water footprint of a Region \(k\) is defined as the amount of water required in order to produce goods for local consumption. This includes locally sourced water for locally produced goods and virtual water which is the embedded water in imported materials. Alternatively, the total production-based water footprint of Region \(k\) will consist only of water utilized in the local production of goods for both local and export consumption. In either case, the total water footprint is the sum of blue, green and gray water. Depending on the specific scenario, any given region within a system may seek to minimize its consumption- or production-based water footprint. It is then assumed that each region will independently set a fuzzy water footprint goal defined by an upper \((WF_k^U)\) and a lower limit \((WF_k^L)\):

$$WF_k^L \leq WF_k \leq WF_k^U \hspace{2cm} \forall k \in K$$  \hspace{2cm} (3)

The degree of satisfaction of each region \((\lambda_k)\) is described by a linear membership function which increases linearly from 0 to 1 as the regional water footprint approaches the minimum footprint \((WF_k^L)\). If the regional water footprint is less than the desired minimum footprint, the goal is fully satisfied and the degree of satisfaction is one. Conversely, if the regional water footprint is greater than the set maximum limit, the degree of satisfaction is zero. This membership function is given by Equation (4) and illustrated in Fig. 1. If the water footprint falls in between the lower
and upper limits, the goal of that particular region will just be partially satisfied.

\[ \lambda_k = \begin{cases} 0 & \text{if } WF_k > WF_{kU} \\ 1 - \frac{WF_k - WF_{kL}}{WF_{kU} - WF_{kL}} & \text{if } WF_{kL} \leq WF_k \leq WF_{kU} \\ 1 & \text{if } WF_k < WF_{kL} \end{cases} \]

(4)

To be able to consider the goals of several regions, fuzzy optimization using max–min aggregation (Zimmermann, 1978) is utilized. The optimization is done by maximizing the degree of satisfaction of the least satisfied participant, and the objective function thus becomes:

\[ \text{max} \lambda \]

(5)

Optimizing \( \lambda \) is subject to the following constraints. First, the overall level of satisfaction maximizes the satisfaction of the least satisfied participant (region):

\[ \lambda \leq \lambda_k \quad \forall k \in K \]

(6)

The range of this overall level of satisfaction is restricted to:

\[ \lambda \in [0, 1] \]

(7)

If several regions are considered, variations in technology and the exchange of materials and products between regions must be accounted for. Equation (1) is thus modified into Equation (8). The technology matrix for Region \( k \), \( A_k \) consists of rows representing economic flows \( i \) which may be products, by-products or resources (e.g., raw materials and energy inputs) of existing processes (represented by column \( j \)). Entries in the matrix \([a_{ij}k]\) represent the amount of economic flow \( i \) required or produced by process \( j \) in Region \( k \). Negative entries indicate input requirements while positive entries indicate output. It is possible that the technology coefficients vary between regions. The vector \( s_{k}^{C_{i}} \) consists of non-negative scaling factors \( \{s_{j}k\} \) (Equation (9)) which indicate the required magnitude for processes in Region \( k \) to satisfy the demand for products of Region \( k' \). Vector \( f \) in this case is no longer the final demand vector but becomes an intermediate output vector of products in Region \( k \) and may contain positive or negative entries to indicate the availability or deficiency of raw materials/products in Region \( k \) to supply Region \( k' \). The resulting intermediate output vector \( \{f_{k}k\} \) indicates the output of products in Region \( k \) which will be utilized to satisfy the demand of Region \( k' \).

\[ A_k s_{k}^{C_{i}} = f_{k}k \quad \forall k, k' \in K \]

(8)

\[ [s_{j}k] \geq 0 \quad \forall j \in J; \forall k, k' \in K \]

(9)

The final demand vector of products for each region is then defined by vector \( y_k \) and is given in Equation (10). The entries \( \{y_{i}k\} \) in matrix \( y_k \) indicate the demand of material \( i \) in Region \( k \) and must all be non-negative (Equation (11)). In order to meet the demand of Region \( k \), resources, products and/or by-products may be sourced locally or imported from other regions.

\[ y_k = \sum_{k'} f_{k}k \quad \forall k, k' \in K \]

(10)

\[ |y_{i}k| \geq 0 \quad \forall i \in I; \forall k \in K \]

(11)

Furthermore, the water footprint of a region will consist of the water footprints resulting from all activities required to satisfy its demand for products. Matrix \( B_k \) contains the water flows (indicated by the rows) associated with the same processes (columns) in matrix \( A_k \). Each entry \( \{b_{ij}k\} \) in matrix \( B_k \) then indicates the amount of water flow \( e \) resulting from the activities of plant \( j \) located in Region \( k \). For this case work, the flows considered are the components which make up the water footprint (e.g., blue, green and gray water). The footprint of a region’s demand for products may impact its local environment or that of a different region (if materials are imported) and since intensity levels of water use vary between regions, Equation (2) is modified into Equations (12a) and (12b). Equation (12a) accounts the water footprint generated in Region \( k' \) due to the demand for products of Region \( k \). The associated footprint from a consumer’s point of view, in this case Region \( k \), is given in the consumer’s water footprint vector \( g_{k}^{C_{i}} \). Alternatively, the footprint based on the perspective of a producer is given by the producer’s water footprint vector \( g_{k}^{P} \), which is given in Equation (12b). In contrast to Equation (12a), Equation (12b) accounts for the total water footprint generated by consumption in Region \( k' \) which includes imports from another Region \( k \).

\[ B_k s_{k}^{C_{i}} = g_{k}^{C_{i}} \quad \forall k, k' \in K \]

(12a)

\[ B_k s_{k}^{P} = g_{k}^{P} \quad \forall k, k' \in K \]

(12b)

The total water footprint for Region \( k \), which is the sum of the water footprints generated in all the regions to satisfy its demand for products, is given by the consumer’s impact vector \( m_k \) as shown in Equation (13a). Similarly, the total water footprint of any Region \( k \) due to production activities performed within the region to satisfy the demand for products of other regions is given by the producer’s impact vector \( z_k \) as given in Equation (13b).

\[ m_k = \sum_{k'} N_{k'k} g_{k}^{C_{i}} \quad \forall k, k' \in K \]

(13a)

\[ z_k = \sum_{k'} N_{k'k} g_{k}^{P} \quad \forall k, k' \in K \]

(13b)

The total water footprint of a region or a product considers the three components, blue, green and gray water. The significance of these components in evaluating the total water footprint can be expressed by assigning weights to the individual components. The weights are represented by the weighting factor vector \( q \). The total water footprint of each region is then obtained either by Equation (14a) or Equation (14b) where Equation (14a) accounts for the water footprint based on the consumer’s perspective and Equation (14b) accounts for the water footprint based on the producer’s perspective. For the purposes of this study, the weighting factors assigned to the three components of the water footprint are all equal to 1, thus \( q = (1, 1, 1) \).

\[ WF_k = q(m_k) \quad \forall k \in K \]

(14a)
It can be seen that this is a linear programming (LP) model, and hence finding the global optimum presents no significant computational difficulties, provided that such a solution exists. However, degenerate solutions may also exist, such that different allocation schemes achieve equivalent levels of satisfaction of the fuzzy goals and constraints. Next, the optimization model is applied to two case studies illustrating consumer- and producer-based water footprints.

5. Case study 1

The first case study demonstrates the optimization of the water intensity of industrial activities when considering the product supply chain from a consumer-based perspective. The model is used to identify the optimal network for material exchange between regions having similar industries but with different technological specifications while simultaneously satisfying the demand for products of each region and under water footprint constraints. This case considers the tile manufacturing industry from Italy (Albino and Kuhrtz, 2004; Kuhrtz et al., 2010), which typically consists of five production processes, namely: mixing, pressing and drying, glazing, cooking, and packaging. It is assumed that the production processes occur in separate production plants. It is further assumed that each manufacturing plant has only one main product. The main product of each plant is given in Table 1. Plant A manufactures clay mixture (CM) which is then utilized by Plant B to produce dried tiles (DT). Dried tiles are then used by Plant C to produce glazed tiles (GT), Plant D then uses the glazed tiles to produce cooked tiles (CT) and finally the cooked tiles are sent to Plant E to produce the final product of packaged tiles (PT). The schematic diagram of the supply chain relating the five plants is given in Fig. 2.

For this case study, three regions are considered in the production of PT. Plant A exists in all three regions but Plants B–E only exists in Region 1. The process data of the plants are shown in Table 2. The columns indicate the plants while the rows indicate the by-products/products considered in the supply chain which may be inputs or outputs of the processes indicated in the column. A negative entry in Table 2 indicates consumption of the product given in the row by the corresponding plant given in the column. Plant B in Region 1 for example, requires 28,430 tons/year of CM to contribute in the packaged tile production of 26,699 tons per year of PT. If the CM is only sourced from Plant A in Region 1, manufacturing 26,699 tons of PT will have a base case water footprint equivalent to 25,523 tons. Region 1 intends to reduce its water footprint by about 25% (or between 20,000 and 23,000 tons) by utilizing less water-intensive raw materials. It is possible to source these materials from other regions if the materials can be produced with a less water-intensive process in other regions. The regional water footprint is then the sum of the blue and gray water required for the production of materials consumed by the region.

Each region has a demand for PT and has identified its fuzzy water footprint goals, which are shown in Table 4. Region 1 requires 26,699 tons per year of PT. If the CM is only sourced from Plant A in Region 1, manufacturing 26,699 tons of PT will have a base case water footprint equivalent to 25,523 tons. Region 1 intends to reduce its water footprint by about 10–25% (or between 20,000 and 23,000 tons) by utilizing less water-intensive raw materials. It is possible to source these materials from other regions if the materials can be produced with a less water-intensive process in other regions. Regions 2 and 3 require 15,000 tons and 10,000 tons of PT respectively. Both regions manufacture CM but not PT. PT can only be obtained from Region 1. Region 2 has set its fuzzy water footprint goals between 10,000 and 14,000 tons per year while Region 3 has set its goals between 6000 and 10,000 tons per year. CM may be obtained from any of the three regions.

The optimal solution is obtained by solving Equation (5) subject to Equations (6–11), (12a), (13a), (14a) and (15). A total production of 55,050.85 tons per year of CM is needed in order to produce 51,699 tons per year of packaged tiles for the three regions. About 74% of the CM is obtained from Region 2 while the rest is obtained from Region 3. The allocation of clay material between each region is given in Table 5. This table shows that Region 2 manufactures 15,599.52 tons per year of CM to contribute in the packaged tile requirement of Region 1. The remaining CM requirement of Region

\[
WF_k = q(z_k) \quad \forall k \in K
\]

\[(14b)\]

\(E\) Packaging packaged tiles (PT)  
\(D\) Cooking cooked tiles (CT)  
\(C\) Glazing glazed tiles (GT)  
\(B\) Pressing and drying dried tiles (DT)  
\(A\) Mixing clay mixture (CM)

For this case study, it is assumed that the dilution factor \(c\) is equal to 1, thus gray water will be equal to the amount of effluent or wastewater generated by the plant. This particular scenario occurs when the pollution load in the effluent is equivalent to the existing quality standard of the receiving body of water (Hoekstra et al., 2009). The regional water footprint is then the sum of the blue and gray water required for the production of materials consumed by the region.

For this case study, it is assumed that the dilution factor \(c\) is equal to 1, thus gray water will be equal to the amount of effluent or wastewater generated by the plant. This particular scenario occurs when the pollution load in the effluent is equivalent to the existing quality standard of the receiving body of water (Hoekstra et al., 2009). The regional water footprint is then the sum of the blue and gray water required for the production of materials consumed by the region.

Each region has a demand for PT and has identified its fuzzy water footprint goals, which are shown in Table 4. Region 1 requires 26,699 tons per year of PT. If the CM is only sourced from Plant A in Region 1, manufacturing 26,699 tons of PT will have a base case water footprint equivalent to 25,523 tons. Region 1 intends to reduce its water footprint by about 10–25% (or between 20,000 and 23,000 tons) by utilizing less water-intensive raw materials. It is possible to source these materials from other regions if the materials can be produced with a less water-intensive process in other regions. Regions 2 and 3 require 15,000 tons and 10,000 tons of PT respectively. Both regions manufacture CM but not PT. PT can only be obtained from Region 1. Region 2 has set its fuzzy water footprint goals between 10,000 and 14,000 tons per year while Region 3 has set its goals between 6000 and 10,000 tons per year. CM may be obtained from any of the three regions.

The optimal solution is obtained by solving Equation (5) subject to Equations (6–11), (12a), (13a), (14a) and (15). A total production of 55,050.85 tons per year of CM is needed in order to produce 51,699 tons per year of packaged tiles for the three regions. About 74% of the CM is obtained from Region 2 while the rest is obtained from Region 3. The allocation of clay material between each region is given in Table 5. This table shows that Region 2 manufactures 15,599.52 tons per year of CM to contribute in the packaged tile requirement of Region 1. The remaining CM requirement of Region

![Fig. 2. Schematic Diagram of Packaged Tile Production Supply Chain.](image-url)
1 is satisfied by the production of 12,830.48 tons per year of CM in Region 3. The water footprint associated in the production of 26,699 tons per year of PT for Region 1, is 21,459.41 tons per year, which corresponds to a 16% reduction from its base case water footprint when CM is not imported from any region. This water footprint consists of the associated blue and gray water within the region and from other regions to provide for the PT requirement of Region 1. Twenty-five percent of the water footprint in Region 1 occurs within the region itself. This means that local resources were utilized and wastewater was discharged within the region to provide for the PT requirement of Region 1. On the other hand, 41% of the water footprint associated to Region 1 is due to the importation of CM from Region 2 and 34% because of the importation from Region 3. These indicate that the environmental burden associated to the requirement of Region 1 occurred outside Region 1. To produce 15,000 tons of PT for Region 2 the water footprint is 11,945.89 tons, 25% of which is due to the production of PT from Region 1 involving process plants B–E, 68% from the production of CM from Region 2 and 7% from CM production in Region 3. Finally to produce 10,000 tons of PT for Region 3, the associated water footprint is 7945.89 tons, 25% of this water footprint is due to the production processes carried out in Region 1 to manufacture PT and 75% due to the production of CM from Region 1. The water footprint allocation due to the exchange of materials between regions is summarized in Table 6. Each entry in this table indicates the water footprint due to the activities performed in the region given in each row, to provide the PT requirement of the region indicated by the column. In addition to these, the last column of Table 6 shows the water footprint associated with the production of goods in the region indicated in each row to provide for the requirements of the three different regions, while the last row indicates the total water footprint associated to each region due to its consumption of PT. All the PT are manufactured in Region 1. However, the CM required as input in process plant B in Region 1 is imported from Regions 2 and 3. The water footprint associated with the activities performed in Region 1, which includes processes B–E, is 10,369.24 tons. On the other hand, Region 2 manufactures a total of 40,801.58 tons per year of CM which has an associated yearly water footprint of 22,761.21 tons. Finally, Region 3 provides 14,249.27 tons per year of CM that have been cited include increased energy security for oil-importing countries, as well as job creation and economic stimulation for the agriculture-based economies in developing countries. The global response has come in the form of increased production and use of biofuels, often accompanied by government mandates specifying blending rates with conventional fuels (Demirbas, 2009; Phalan, 2009; Yan and Lin, 2009; Zhou and Thomson, 2009). Despite the benefits arising from the production and use of biofuels, significant costs may also be incurred by an indiscriminate shift towards massive production levels (Florin and Bunting, 2008; Stoeglehner and Narodoslawsky, 2009). It has been argued that the limited availability of agricultural land imposes constraints on the production of biofuels for specific countries (e.g., Ponton, 2009; Zah and Ruddy, 2009) or on a global scale (Nonhebel, 2005). Likewise, the limited availability of water is expected to be a major challenge, particularly as climate change results in shifts in rainfall patterns across the world (Berndes, 2002; Gerbens-Leenes et al., 2009). Thus, it is now clear that the potential gains from large-scale bioenergy production and use come only at the expense of significant demands on agricultural resources.

For the production of biofuels, unlike the previous case study, green water becomes significant in establishing the water footprint of the product since the main raw material is an agricultural item. Different methodologies have been used to provide decision support for planning bioenergy production under resource constraints, including pinch analysis (Tan and Foo, 2007; Foo et al., 2008; Lee et al., 2009; Tan et al., 2009a), input–output analysis.

### 6. Case Study 2

The second case study is focused on the production of biofuels whose popularity has grown due to climate change and the increase in the price of conventional fossil fuels. Ecological footprints for bioenergy systems have been estimated to be about one order of magnitude lower than those of corresponding fossil fuels (Stoeglehner and Narodoslawsky, 2009). Other secondary benefits that have been cited include increased energy security for oil-importing countries, as well as job creation and economic stimulation for the agriculture-based economies in developing countries. The global response has come in the form of increased production and use of biofuels, often accompanied by government mandates specifying blending rates with conventional fuels (Demirbas, 2009; Phalan, 2009; Yan and Lin, 2009; Zhou and Thomson, 2009). Despite the benefits arising from the production and use of biofuels, significant costs may also be incurred by an indiscriminate shift towards massive production levels (Florin and Bunting, 2008; Stoeglehner and Narodoslawsky, 2009). It has been argued that the limited availability of agricultural land imposes constraints on the production of biofuels for specific countries (e.g., Ponton, 2009; Zah and Ruddy, 2009) or on a global scale (Nonhebel, 2005). Likewise, the limited availability of water is expected to be a major challenge, particularly as climate change results in shifts in rainfall patterns across the world (Berndes, 2002; Gerbens-Leenes et al., 2009). Thus, it is now clear that the potential gains from large-scale bioenergy production and use come only at the expense of significant demands on agricultural resources.
(IOA) (Turner et al., 2007), system perturbation analysis (SPA) (Bram et al., 2009), ecological footprinting (Stoeglehner and Narodoslawsky, 2009), life cycle assessment (LCA) (Udo de Haes and Heijungs, 2007; Tan et al., 2009b) and hybrid graphical/optimization approaches (Lam et al., 2010).

As in the first case study, each region has specified fuzzy limits on the identified environmental footprints. In addition to this, each region has also specified fuzzy limits on the final demand for a set of biofuels. Agricultural and process yields are known as defined in the form of technological coefficients. Each region may produce feedstocks internally in order to satisfy its final biofuel demand. It may also select to import (in the case of local deficit) or export (in the case of local surplus) biomass, depending on the internally specified footprint limits. In this case study, the footprint limits are based on the available resources of the regions and are thus producer-based water footprint limits. The problem is to determine the optimal production and trade levels to satisfy the fuzzy fuel demand and fuzzy resource constraints of the regions that comprise the overall system. The objective is to maximize the overall level of satisfaction, as is given in Equation (5) and is subject to the constraints given in Equations 4, 6—11, 12, 13, 14b and 16—18.

The intermediate output vector of raw materials and products from Region \( k \) for Region \( k' \) is again given by Equations (8) and (9), and \( f_{lk} \) represents the availability (positive values) or deficiency (negative values) of Region \( l \) to supply the demand required by Region \( k \). Each region has specified fuzzy limits for the demand of products which may be manufactured locally or imported from other regions. The optimization is thus subject to the constraint given in Equation (10) such that locally produced and imported biomass or biofuel product is sufficient to meet the fuzzy final demand for biofuel products. Here, the final demand of the regions are given by fuzzy limits identified by a lower demand limit \( (y^l_k) \) which is the least acceptable amount of the final demand, and a tolerance \( (\Delta y_k) \) which indicates the acceptable range in final demand. The maximum ethanol demand is then defined by:

\[
y^U_k = y^l_k + \Delta y_k \quad \forall k \in K
\]

The overall level of satisfaction must satisfy the demand objectives of the individual participants and must thus be satisfied to at least the degree \( \lambda \) given in Equation (17).

\[
\lambda \leq \begin{cases} 
0 & \text{if } y_k < y^l_k \\
\frac{y^U_k - y^l_k}{y^U_k - y^l_k} & \text{if } y^l_k \leq y_k \leq y^U_k \\
1 & \text{if } y_k > y^U_k 
\end{cases} \quad \forall k \in K
\]

It can be seen that the production level is at the less desirable lower limit for \( \lambda = 0 \), and approaches the more desirable upper limit as \( \lambda \) approaches 1. This case study is concerned with the environmental constraints in a region that will limit the capability of a region to produce biomass. Thus this requires a production-based perspective to evaluate the ecological footprint of the activities in a region. The environmental flow vector based on a production-based perspective of any producing Region \( k \) is given by \( g^P_k \), as shown in Equation (12b). The right side of Equation (12b) pertains to the environmental impact experienced by Region \( k \) as a producer to satisfy the requirements of Region \( k' \).

Total internal production of biomass, within a given Region \( k \) is subject to fuzzy environmental constraints that reflect flexible limits on resources and emissions. The environmental constraint here corresponds to limitations in available water resources. The total environmental burden associated to the internal production of biomass is given by the producer’s impact vector \( z_k \) and is shown in Equation (13b). For this case study, the main concern is the availability of water resources in a region to facilitate the production of crops required for biofuel manufacturing. Thus, the total water footprint based on the producer’s perspective is utilized and is as given in Equation (14b). For this case study, it is assumed that the total water footprint mainly consists of green and blue water associated for the growth of crops. Furthermore, the water footprint constraint is again represented by fuzzy limits defined by an upper limit \( (W^U_k) \) which is the maximum allowable water footprint due to the production of goods in Region \( k \) to provide for the

### Table 7: Regional Final Ethanol Demand in Case Study 2.

<table>
<thead>
<tr>
<th>Region</th>
<th>Lower limit (10^6 L per year)</th>
<th>Tolerance (10^6 L per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>211</td>
<td>211</td>
</tr>
<tr>
<td>II</td>
<td>52.5</td>
<td>52.5</td>
</tr>
<tr>
<td>III</td>
<td>58.8</td>
<td>58.8</td>
</tr>
</tbody>
</table>

### Table 8: Regional Water Availability Limits in Case Study 2.

<table>
<thead>
<tr>
<th>Region</th>
<th>Upper limit (10^6 tons per year)</th>
<th>Tolerance (10^6 tons per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1200</td>
<td>800</td>
</tr>
<tr>
<td>II</td>
<td>450</td>
<td>300</td>
</tr>
<tr>
<td>III</td>
<td>607</td>
<td>303.5</td>
</tr>
</tbody>
</table>
requirements of all regions and the water footprint tolerance \((\Delta \text{WF}_k)\) which indicates the acceptable producer-based water footprint range. The desired water footprint \((\text{WF}_k^*)\) is obtained by subtracting the tolerance from the maximum allowable burden as given in Equation (18).

\[
\text{WF}_k^U - \Delta \text{WF}_k = \text{WF}_k^* \quad \forall k \in K
\]  

Again, the overall level of satisfaction must satisfy the environmental constraints up to at least the degree \(c\) subject to the constraint given in Equation (4). The footprint levels are at the less desirable upper limits for \(c = 0\), and approach the more desirable lower limits as \(c\) approaches 1. Matrices \(A_k\) and \(B_k\) signify the processing and agricultural yields, respectively, in a given Region \(k\). These yields are assumed to be constant, and may be determined from first principles or, alternatively, derived empirically from historical data. It can also be seen that the yields may or may not be the same across the different regions. Finally, the biomass and biofuel production \((\text{Sk}_k)\) and requirement \((y_k)\) levels within each region are non-negative as given in Equations (9) and (11), respectively.

This case study is based on ethanol production scenarios in the Republic of the Philippines (Foo et al., 2008; Tan et al., 2009a), where legislation on the use of biofuels for transportation was recently enacted. The fuels that have been identified for the biofuel program are ethanol (derived from sugar- or starchy-bearing food crops such as sugarcane and corn, respectively) and biodiesel (derived from oil-bearing crops such as coconut). Table 7 shows the lower limits and fuzzy tolerances of annual ethanol demands in the three major geographic regions of the country. Both the lower limits and tolerances correspond to the displacement of 5% of gasoline demand, hence resulting in upper limits that correspond to 10% ethanol substitution rates (see Equation (16)). Note that the ethanol demand in Region 1 is disproportionately large; the imbalance results from differences in the levels of population and economic development across the different regions of the country. There are more large urban and industrial centers in Region 1 than are found in Regions II or III, and thus its energy requirements are significantly larger.

The feedstocks being considered here for ethanol production are sugarcane and corn. These are currently staple crops in the Philippines, and are thus available in sufficient quantities to minimize the sort of difficulties that arise in nascent bioenergy supply chains, such as supply volatility (Cruz et al., 2009). The water footprints for sugarcane and corn, which are primarily green and blue water necessary for plant growth, are 2.43 and 3.29 tons of water per liter of ethanol equivalent respectively. These figures are similar to those found in previous papers (Foo et al., 2008; Tan et al., 2009a). Note that the values given are based on one unit of final ethanol equivalent, rather than on one unit of raw biomass. Table 8 shows the water resources available in the three regions. The water resources used here have been adjusted relative to the original values (Tan et al., 2009a) to account for regional differences in precipitation levels which vary from 1000 to 2000 mm per year.

Solving the optimization model with these data gives the final regional production and trade values shown in Table 9. In the optimal solution, \(c = 0.674\), such that the final fuel production and water footprint levels lie slightly towards the desired production level and water footprint limits previously specified. Furthermore, all of the ethanol across the three regions is derived solely from sugarcane, which requires less water inputs per unit of ethanol equivalent than does corn. It can also be seen in this particular solution that Region I is a net importer while Regions II and III are net exporters of biomass for Region I. Region I obtains 77% of its requirements from local production, about 4% from Region II and the remaining 19% from Region III. Region II utilizes 86% of its production for local consumption and exports the remaining 14% to Region I. Region III on the other hand uses 60% of its production for local consumption while the remaining 40% is exported to Region I. This result reflects the imbalances between energy demand (which are largely a function of population size and economic affluence) and resource availability (which is determined here by precipitation levels) across the three regions. Clearly, such imbalances also occur on much larger geographic scales, for example across different countries or continents (Fig. 4).

---

**Table 9**

Final Regional Production and Trade Levels in Case Study 2.

<table>
<thead>
<tr>
<th>Source Region</th>
<th>Internal Production</th>
<th>Demand Region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>271.94</td>
<td>271.94</td>
</tr>
<tr>
<td>II</td>
<td>101.97</td>
<td>14.09</td>
</tr>
<tr>
<td>III</td>
<td>165.61</td>
<td>67.18</td>
</tr>
<tr>
<td>Total Demand</td>
<td>353.21</td>
<td>87.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>II</td>
</tr>
<tr>
<td></td>
<td></td>
<td>101.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>87.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>98.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>III</td>
</tr>
<tr>
<td></td>
<td></td>
<td>67.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>98.43</td>
</tr>
</tbody>
</table>

*Figures in 10³ L per year of sugarcane ethanol.*
7. Conclusion

A multi-regional fuzzy input–output model has been developed to optimize production and trade under consumption- or production-based water footprint constraints. The approach makes use of scale-invariant technological coefficients and max–min aggregation to yield a linear programming model for which a global optimum may be easily determined. Two case studies have been used to demonstrate the capability of the model in identifying the optimal network of material/product exchange between different regions to satisfy the regional demand for products and achieve consumption- or production-based water footprint goals. The model simultaneously considers the fuzzy goals set by several regions/stakeholders or decision-makers at either enterprise-level or regulatory-level contexts. Furthermore, the model can be used for assessing the ecological footprint of activities associated to an enterprise or region in the consumer or producer’s perspective as demonstrated in case studies. This is significant in allocating environmental responsibility between the consumer and the producer. Further extensions of this model may then be developed to account for environmental footprints other than water; dynamic problem aspects (e.g., energy demand growth or efficiency improvements due to technological progress); and parametric uncertainties in the technological coefficients.

Acknowledgment

The authors are grateful for financial support through the Graduate Fellowship Program of De La Salle University.

Nomenclature

Sets

\( K \) \{k is a region\}, \( k = 1, 2, 3, \ldots, N_K \)
\( E \) \{e is an environmental intervention\}, \( e = 1, 2, 3, \ldots, N_E \)
\( I \) \{i is a resource/by-product/product\}, \( i = 1, 2, 3, \ldots, N_I \)
\( J \) \{j is a plant/process\}, \( j = 1, 2, 3, \ldots, N_J \)

Indices

\( e \) index for water flow
\( i \) index for raw material/product
\( j \) index for process/plant
\( k \) index for regions

Parameters

\( N_E \) number of environmental interventions being considered
\( N_J \) number of economic flows
\( N_I \) number of plants/processes
\( N_K \) number of regions
\( N_{IK} \) number of products in Region \( k \)
\( N_{IK} \) number of plants/processes in Region \( k \)

Variables

\( \lambda_k \) degree of satisfaction achieved by Region \( k \)
\( A \) \([a_{ij}]\) technology matrix for inputs/outputs of product \( i \) in plant \( j \)
\( A_k \) \([a_{ij}]\) technology matrix for inputs/outputs of product \( i \) in plant \( j \) in Region \( k \)
\( B \) \([b_{ij}]\) environmental matrix containing the environmental flow \( e \) from each plant/process \( j \)
\( B_k \) \([b_{ij}]\) environmental matrix containing the environmental flow \( e \) associated to plant \( j \) in Region \( k \)
\( c \) dilution factor relating wastewater to gray water

\( f \) \([f_i]\) the final output vector of product \( i \)
\( f_{ij} \) intermediate output vector containing surplus/deficiency of product \( i \) in Region \( k \) to supply demand of Region \( k' \)
\( g \) \([g_i]\) inventory vector containing the total of each environmental flows \( e \)
\( s \) \([s]\) consumer’s environmental flow vector which contains the environmental burden associated with the products manufactured from Region \( k' \) but used by Region \( k \)
\( m_k \) producer’s environmental flow vector which contains the environmental burden associated with the products manufactured in Region \( k \) but will be used by Region \( k' \) \([m_{ij}] \) is the consumer’s impact vector, it contains the environmental burden associated with the demand for products of Region \( k \)

\( GW \) volume of gray water
\( q_i \) \([q_i]\) weighting vector
\( s_i \) scaling factor for each plant/process \( j \) to achieve final product output
\( s_{kj} \) \([s_{kj}] \) scaling factor vector for plant/process \( j \) in Region \( k \) to supply demand of Region \( k' \)
\( \text{WF}_k \) water footprint of Region \( k \)
\( \text{WF}_k^j \) lower limit of water footprint goal specified by Region \( k \)
\( \text{WF}_k^{xj} \) upper limit of water footprint goal specified by Region \( k \)
\( \Delta \text{WF}_k \) tolerance of water footprint limit in Region \( k \)
\( \text{WW} \) volume of wastewater
\( y_{ij} \) \([y_{ij}] \) final demand vector of product \( i \) in Region \( k \)
\( y_{ik} \) lower bound of final demand vector in Region \( k \)
\( z_k \) producer’s impact vector, contains the total environmental burden experienced by Region \( k \) to provide for the requirements of all regions

References
