Methodology to judge biorefinery options in a bioenergy production chain

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Preface

This project was conducted for FACT-Foundation by Igor Milosavljević as an Internship for his MSc program at Wageningen University. Winfried Rijssenbeek from FACT Foundation and Gerrie van de Ven from Plant Production Systems in Wageningen University and Researchcentre supervised. This work was commissioned by Winfried Rijssenbeek of FACT-Foundation.

Summary

Local bioenergy projects can galvanize rural development and improve livelihoods. Biorefinering can also improve local incomes. This work aims to present a methodology to judge the People Planet Profit prospects of a proposed biorefinery operation in a bioenergy production chain. The first step involves making a flow chart; it can be used to recognize biorefinery options and estimate the Profit generated by the proposed operation. The second part involves using a Fuzzy Cognitive Map (FCM), a semi-quantitative tool; it can be used to examine effects on People and Planet. There are some analytical tools described for use in the FCM. Final People, Planet and Profit results can be compared for different options. The methodology described guides a cognitive process to consider different biorefinery options in a bioenergy chain. It is suitable for use in rural areas of developing countries.

1 - A Vast Challenge, A Great Opportunity

Industrialized human well-being is dependent on petroleum and other non-renewable fossil sources to a large extent for the provision of basic goods and services: heat, electricity, mechanical energy, chemicals, pharmaceuticals, fibers, plastics, transportation, and inputs in food production. The comfort and productive potential of the fossil-dependent livelihood is unmatched by other alternatives on a large scale.

Reliance on non-renewables has important weaknesses. Fossil sources have inevitable physical limits. Their use causes negative environmental impacts, e.g. global warming, acidification of oceans, air pollution. The price of petroleum, the base-input for the paramount petrochemical industry, has become high, volatile, and hence suboptimal for economic and security considerations; the root causes, economic expansion from developing countries and geopolitical instability of oil producers, are unlikely to abate in the medium run. To safeguard present livelihoods and offer development pathways for non-industrialized societies, more sustainability is needed; in part, this requires using renewable materials and minimizing waste.

Few steps have been made towards the modern biorefinery, particularly in the developing world. With lack of experience to draw upon, a tool or methodology is needed to judge biorefinery options to aid decision making. This work aims to develop a guiding process to:

- stimulate and structure cognition to understand a proposed biorefinery system in the wider nested reality, and,
- to provide a framework to compare different options and identify tradeoffs,

with People-Planet-Profit as a measure of achievement in the operational context of FACT Foundation, i.e. rural communities in developing countries.

2 - Background: The Facts

2.1 - Sustainability: People Planet Profit

Sustainability entails production without adversely affecting resources and conditions so as to damage the ability for consecutive reproduction. The concept has roots in the mid- 20th century when social consciousness of the environmental damage from industrialization formed. The United Nations (UN) Conference on the Human Environment (1973) brought these concerns into the mainstream. Following up, the Brundtland Commission was given the task to examine environmental and developmental issues and propose a new orientation for future efforts; they concluded that development "rests on the environment" (UN, 1987). As a result, sustainability was adopted as a guiding principle of the UN in Resolution 42/187 during the 96th Plenary Meeting of the General Assembly. Agenda 21 (UN, 1992) was formed during the UN Conference on Environment and Development as an action plan for the UN, international agencies and national governments to address sustainability.

People Planet Profit is a criteria framework for sustainability performance measure of a project or entity (corporation, country, etc.). The framework's three sections attempt to account for the full scope of the concept: socioeconomic (e.g. human rights, access to healthcare, social cohesion, tradition), environmental (e.g. soil quality, toxic substance emission, air pollution) and financial (e.g. profits, revenue per kW, return on investment).

2.2 – Bioenergy and Biorefining

- *2.2.1 Definitions*

Bioenergy is heat, light, electricity or mechanical energy intentionally released from biological sources by humans for their purposes. Bioenergy is renewable, as its sources harness the functionally endless energy of the sun. Although bioenergy can also include heat from firewood or animal faeces, its contemporary use largely denotes modern processed forms such as bioethanol, biodiesel, green diesel, biogas, etc.

Bioethanol is currently the primary bioenergy carrier. It has a decades long history of use in Brazil where sucrose rich sugarcane provides a good industrial feedstock (BNDES et al., 2008). The world's second producer is the United States of America where maize is used as a feedstock. Maize is rich in starch, which has to be has to undergo hydrolysis to glucose before it is fermented with baker's yeast. Biodiesel is also significant, produced by transesterification of plant glycerides to fatty acid methyl esters. Bioethanol and biodiesel mostly use crops which are edible and have stirred controversy in regards to possible effects on food security. Biogas is also noteworthy as its small scale use is widespread, in both developed and developing countries (Ghimire, 2013). Biogas is obtained by anaerobic digestion of organic material by methanogenic bacteria.

Biorefining is the process of converting biological materials into fuels, energy, heat, fibers, feed, food, cosmetics, chemicals and pharmaceuticals. Classical examples have existed for some time, such as paper pulping. Advanced forms, currently being developed, utilize novel processes to partition biomass feedstock, or fractionize, and separately process these elements for multiple products for multiple ends (de Jong et al., 2010). In this way, the modern biorefinery concept is similar to the petrochemical refinery, an institution it is posed to replace in a biobased economy.

- *2.2.2 Biomass as an Industrial Feedstock*

In the shift towards a bio-based economy, use of biomass is requisite. Widely and abundantly available (Langeveld, 2010), biomass is the only carbon-rich material apart from fossils (Ghatak, 2011). It is hence the only renewable material that can replace fossil-sources as a base-input in the production of the current range of goods and services; the biorefinery in place of the petrochemical refinery.

Similar to fossils, biomass is heterogeneous. Terrestrial biomass is composed of:

- fat (triglycerides),
- carbohydrates (e.g. hexoses, pentoses, disaccharides, starch, non-starch polysaccharides)
- lignocellulose (lignin, cellulose, hemicelluloses),
- proteins (amino acids),
- other organic compounds (e.g. vitamins, alkaloids, other lipids),
- and ash (minerals).

Before industrialization, and indeed throughout it (Nelson et al., 2011), plant components have been separated and processed for the various applications. Powell et al. (2011) provide a good summary of current industrial uses of oils, sugars and starches, and lignin from lignocellulose:

- Biomass derived oils are processed into biodiesel, glycerin, coatings, polyurethane, inks, lubricants, emulsifiers, commodity and specialty chemicals, and for cosmetic applications.

- Biomass derived sugar and starch are processed into ethanol, biobutanol, solvents (propanediol, furfural as intermediate), intermediate chemicals, lysine (used as a feed additive and in pharmaceuticals), aromatics (caprolactam, phloroglucinol, shikimic acid, resorcinol), cosmetic applications (ex. glycolic acid), plastic material (polylactic acid), fibres (nylon, polyester), food sweeteners (aspartic acid, xylitol, sorbitol), monosodium glutamate, food preservative (citric acid), food acidulant (citric acid, gluconic acid), antioxidant food additive (sodium erythorbate).
- Biomass derived lignin is processed into chemicals such as vanillin, adhesives, binder in composites, polyurethane coatings, flame retardants, brake pads, carbon fibers, concrete additive (lignosulfinate), energy and heat from combustion, animal feed additive, human nutritional supplements.

Proteins, useful organic compounds, and ash are useful as feed additives, as food additives and as chemical products and intermediaries. Composed of plant macro and micro nutrients, ash can be returned to the soil as a fertilizer for plants.

There is a wide array of pathways to process biomass components available for the biorefinery; figure 1 gives an overview. Note that the figure is not complete and that other processes are also available, such as dehydration of fibers for rope weaving or pressing fibers with adhesives to produce boards.

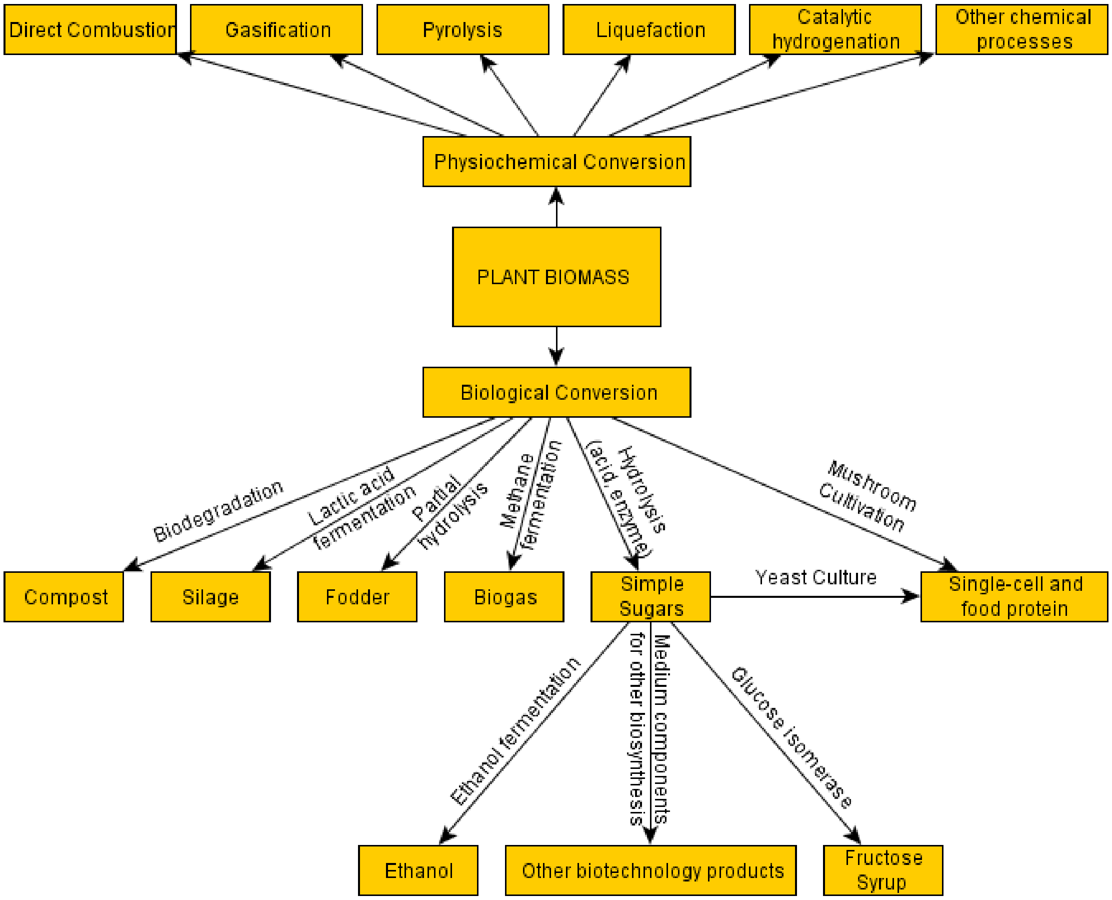


Figure 1. Example biomass utilization pathways, redrawn figure from Szczodrak et al. (1996).

As mentioned before, the modern biorefinery fractionizes biomass into distinct components that are processed into different end products. This entails a production chain, which undergoes multiple biomass utilization pathways from figure 1. Different end products have different market values and quantities demanded, as represented in figure 2.

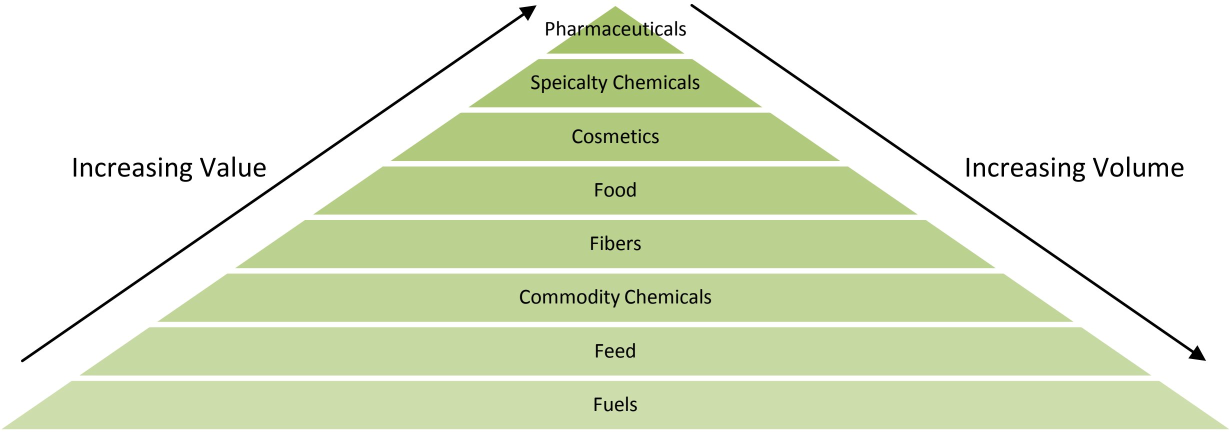


Figure 2. Representation of the indirect market volume and market value relationship for different ends of production. The direction of the arrows represent the direction of increase for value and volume. Diagram is relative, not exact.

If figure 1 and 2 are examined together, it is clear that fuels and other low value products will have restrictions to which transformation routes can be employed in their production, if conducted in isolation. In general, thermochemical conversion pathways involve higher temperatures and pressures (Bakker, 2010) and hence require economies of scale for feasibility, which is a major challenge for biomass feedstock (2.2.4). For this reason, fractionation is important for the economic feasibility of a bio-based industry (Østergård et al., 2010; Sanders et al., 2008), similar to the petrochemical industry. Ragauskas et al. (2006) describe a process wherein value-added components are removed and the residues are consequently processed into bioenergy. Multiple branches on a production chain also grant flexibility and some maneuverability to react to market incentives. For example, Agro2 (www.agro2.com), a FACT Foundation partner in Panama, processes cassava for food as it is more valuable than processing into ethanol; they are currently exploring ethanol fermentation of residues (e.g. peels). The cost of residues is near nil, perfect for low-value ethanol. The question remains to whether this will be viable, with peels containing a heightened concentration of cyanide which might affect the performance of *Saccharomyces cerevisiae* (baker's yeast).

However, till date, biomass component separation on the scale of a petrochemical refinery remains costly (Ragauskas et al., 2006), although continued research, development, and trials are sure to bring costs down.

As an alternative to building from scratch, the modern biorefinery can evolve from current biorefineries and biofuel plants. BNDES et al. (2008) describe sugarcane bioethanol production in large detail. Sugarcane biomass is pressed to collect sugarcane juice, leaving behind solid residues called bagasse. Sugarcane juice can be boiled to crystallize sucrose and separate it from molasses; crystallized sucrose can be further dehydrated to produce sugar. Alternatively, sugarcane juice can be combined with residual molasses to form a mash, which is fermented into ethanol using *Saccharomyces cerevisiae*. Ethanol can be an important platform chemical (Powell et al., 2011; BNDES et al., 2008). Bagasse is normally combusted to produce energy in the form of heat, with excesses sometimes converted into electricity and sold. However, as lignocellulosic material (2.2.3), bagasse can be fractionized into cellulose, hemicelluloses, and lignin portions and transformed into various products (see above).

Alternatively, for example, bagasse can be codigested into biogas before combustion, with residual ash, rich in P and K, returned to sugarcane fields as fertilizer.

There is large interest to make biofuels from lignocellulose. Of all plant components, only lignocellulose is not used as food, and hence is not exposed to the controversy of competing with food. Large quantities are available as waste residues from agriculture, silviculture and urban consumption; lignocellulose is the most abundant material on earth (Langeveld, 2010). Using lignocellulose as a biorefinery feedstock is promising for a sustainable bio-based economy, but not without challenges.

Lignocellulose is a hard structural material used in plant cell walls, see figure 3. Lignocellulose contains hemicelluloses, cellulose and lignin. Cellulose is complex carbohydrate chain that can be broken down into glucose, a simple sugar. Hemicellulose is related to cellulose, but has a heterogeneous chemical structure including other sugars besides glucose. If these carbohydrate chains are isolated from lignin, they can be broken down and used as sugars (see above), including fermentation to ethanol. Lignin is structurally very heterogeneous and recalcitrant to degradation; it serves an important protective role for plants.

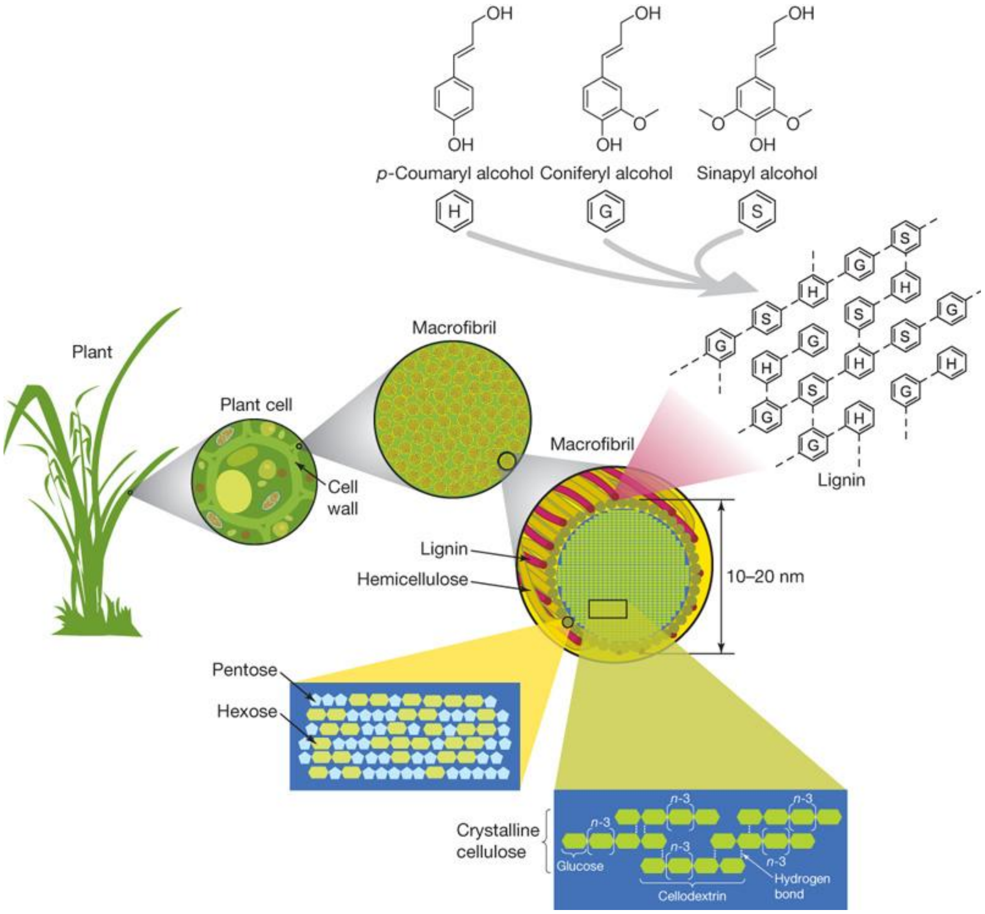


Figure 3. Diagram of lignocellulose's position in the cell walls of plant tissue, its arrangement, and its components from Rubin (2008).

Ethanol from lignocellulose is referred to as second generation biofuel, which has yet to mature beyond the pilot stage due to high costs of current available technologies (BNDES et al., 2008). Other lignocellulose energy carriers are possible by using thermochemical conversion pathways, i.e. pyrolysis and gasification (Bakker, 2010); however, the high temperatures and pressures require large-scale facilities, high transportation costs for feedstock biomass (2.2.4), and high capital costs, making them unlikely solutions for developing countries. Fermentation and digestion require pretreatment steps and high concentrations of enzymes which limit financial feasibility. As such, major breakthroughs are necessary before this technology becomes feasible for use in rural areas of developing countries.

- *2.2.3 Sustainability and Rural Development*

Traditional biorefineries typically specialize on a single output, such as paper production, with disposal or suboptimal utilization of other biomass components. For example, paper pulp mills combust lignin contained in the waste substance, black liquor, for in-house energy needs. Similarly, current large-scale bioenergy production chains mostly use a single crop component rich in fat or carbohydrates: e.g. maize kernels, sugar beet tuber. On a smaller scale, biological materials (i.e. agricultural residues, specialized energy crops, municipal waste, and livestock manure) are digested into biogas.

On a regional scale, striving for greater sustainability will require specific extractive production chains to be altered to use and reuse waste and residue streams to a greater degree. Social benefit from limited biomass can be maximized if use efficiency is increased through reuse, recycling and, lastly, energetic use of materials, referred to as *cascade utilization of biomass* (Haberl et al., 2000). Materials resistant to decomposition or toxic to ecosystem and their inhabitants should be transformed or avoided before being expelled from societal use. These concepts are illustrated in figure 4.

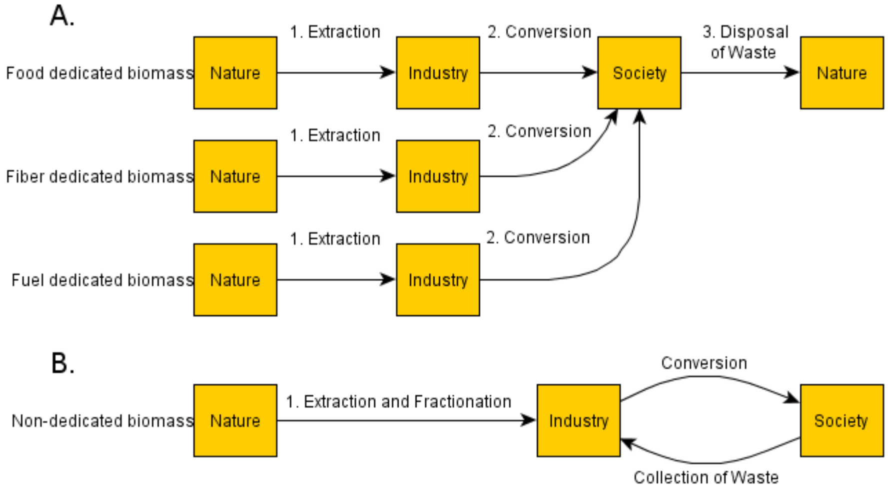


Figure 4. Illustrations of two example production chains to reflect differing paradigms of resource utilization. A. is an extractive extreme wherein food, fiber and fuel are separately extracted from nature, converted for human utility and discarded after use without any regard for biodegradability. B. shows non-dedicated extraction of resources and fractionation, followed by use of waste streams for the production of other products; as an extreme example akin to the cradle to cradle concept, no untreated waste streams are dumped outside of the human sphere.

Lack of energy access can limit and damage human, social and economic development (Ghimire, 2013). In recognition of this, UN Secretary General Ban Ki-Moon (2011) launched Sustainable Energy for All (www.sustainableenergyforall.org). The World Bank has spent $11 billion USD on sustainable energy projects (IBRD, 2011). Similarly, FACT-Foundation operates under the same understanding (http://www.fact-foundation.com/).

Traditional energy sources—wood, charcoal, dried animal faeces, food residues, sunlight—have many drawbacks. Collection time of wood and faeces can be significant, drudgerous, and record little productivity on a marginal scale; competing with alternate ends of labor, including schooling for children (Rao, 1982). Pressure on forest resources can result in a loss of natural wealth, e.g. deforestation, soil erosion, loss of biodiversity, habitat fragmentation. Removal of organic residues and manure from fields forgoes the ameliorating effects on soil physical and chemical properties. Indoor noxious fumes produced by burning these fuels negative consequences for human health.

Modern energy provides electricity and mechanical power. Electric/combustion machinery can be adopted, increasing labour productivity and economic diversification. In this way, modern energy can "attack the root cause of rural poverty", low productivity (Rao, 1982). Moreover, vaccines can be refrigerated locally, nighttime light allows children to study after sundown (Clark, 2012). Enterprise is also enabled: lighting in shops, tailoring with electricity, cell phone charging service, etc.

Biorefineries can also benefit rural development. Biomass has high water weight and low concentration of energy and other elements interesting for extraction. As such, large transport costs create an incentive for at least some degree of processing to occur near the biomass' production location (Papendiek, 2012; Bailey et al., 2011; Arai et al., 2009; Nelson et al., 2011), before feeding into larger scale production facility. In turn, this is projected to increase rural employment and incomes (Krajnc et al., 2007; Bailey et al., 2011; Mayfield et al., 2007). Diversification of rural production will grant greater economic resilience and opportunity in rural areas. Farmers can gain a greater share of final product value by controlling another step in the processing chain (Bruins et al., 2012). By improving their position in the production chain, they will have the incentive to optimize the farm level process as they are able to capture the benefits to a greater degree than presently (Sanders, 2007). More effective utilization of biomass resources will result in less waste streams (Bruins et al.; 2012).

However, decentralization will result in loss of upscaling efficiency (economies of scale) of mass production, particularly when large heat or energy inputs are needed. Moreover, they are yet to be formed on a large scale.

2.3 – Survey of Sustainability Related Scoring Methodologies

Numerous methodologies have been developed to perform sustainability accounting on various levels in various contexts. Certain aspects of sustainability are inherently hard to quantify and remain a challenge. For example, how does one quantify the benefit of social cohesion or tradition for a community? How does one value biodiversity?

In the context of this project, a preliminary exercise is necessary to make judgments about different options. Much work has been done to develop frameworks and tools to conduct such an analysis. Environmental and Social Impact Assessments are used on a local/regional scale to examine projects (Khandker et al., 2010; Glasson et al., 2005; Barrow, 1997; OECD 2007). Strategic Environmental Assessments are used on a national/regional scale to examine the effects of policies and programs and is used by the OECD and UNEP (Dalal-Clayton et al., 2005). The Millennium Ecosystem Assessment was used for a global scale (UNEP et al., 2010). References refer to recommendable guidebooks and manuals. Kee et al. (2003) offer a good review and discussion of sustainability accounting practices for international organizations.

Numerous other methodologies exist for different specific purposes. The ISO 14000 family certifies and monitors environmental management (http://www.iso.org/iso/iso14000) and the ISO 26000 family monitors social responsibility (http://www.iso.org/iso/home/standards/iso26000.htm). The World

Bank's classical cost and benefit analysis has been expanded to monetarize environmental and social aspects (IEG, 2010), albeit seldom with difficulty. Moreover, sustainability accounting services have become widespread in both large and specialized firms: KPMG, Ernst & Young, AcountAbility, SustainAbility, SustainAnalytics, among others. The SEAMLESS project (www.seamless-ip.org), a research consortium on a European level, developed a database of models for ex-ante exploration (Olsson et al., 2009).

In general, the assessment frameworks mentioned above have some degree of requirement for quantitative data. Therefore, they cannot be used for this project.

3 - The Methodology

The methodology consists of two parts. The first part involves making a flow chart of the biorefinery operation and using it as a crutch for financial accounting (3.1). It focuses on the production chain. The second part involves making a fuzzy cognitive map, a type of flow chart, and analyzing it to determine environmental and social effects (3.2). It focuses on the wider system in which the production chain is nested. This methodology is intended to serve as a structured but flexible guideline of a cognitive process which itself should guide more informed decision making.

As an example, a bioethanol production chain will be run through all the steps of the methodology.

3. 1 - Flow Chart and Financial Accounting

The flow chart identifies and structures the production chain. The flow chart can be used to identify different biorefinery options in itself, or can be developed for pre-determined options. In the latter case, the next paragraph can be ignored.

If one would like to use the flow chart to explore what biorefinery options are available, a good starting point is to build a flow chart for the case study's existing production chain. From here, one can see what stocks are available within and at the end of the process, and contemplate alternative uses for them. This would create different production chains that can be analyzed in the consecutive step.

If starting from scratch, a list of inputs and outputs of the productive process is very useful. For inputs and outputs, it is necessary to distinguish between what is variable and what is fixed, as only variable inputs and outputs should be charted. Variable inputs and outputs occur overtime and increase if production increases. For example, labour hours, feedstock, electricity used are all variable inputs that vary with levels of production. Fixed inputs and outputs are one time occurrences, like factory construction and the associated waste, and do not change with changes in production volumes.

Knowing what to include in the flow chart can be tricky. For example, a production system could divert feedstock for dairy livestock feed, and use their faeces for biogas digestion. In this case, it is necessary to know the objective of using the methodology. Is the focus on the community level? If so, then the financial balance can be calculated on this level, including milk and meat sales from the example above. Is the focus on a specific company or organization? In this case, the inputs and outputs of the firm should be the focus, with additional financial effects treated separately. The level of detail and scope should be maintained for all chains of the options being considered to allow for comparison.

The variable inputs and outputs are used to make the flow chart; fixed inputs and outputs will not be considered in the flow chart. Inputs can be placed on the left side of a paper or poster, and outputs on the right. The inputs and outputs represent stock values. A stock can be quantified without a time dimension (kg, ha), as opposed to a flow (kg/hr, ha/yr). Next, the flow chart can be filled in to account for the production process between inputs and outputs. Boxes should be used for intermediary process stocks, and arrows for processes, as in figure 5.

Many different flowcharts can be made to represent the same productive process. It is important that the flowchart reflect reality to a desired degree and focuses on what is important. For example, the flow chart can begin with soil/seeds/water/nutrients/light radiation rather than sugar cane as a primary input; although this agricultural process might not reflect a biorefinery's operation. On the other hand, if feedstock production occurs on plantations owned by the biorefinery, it might be appropriate.

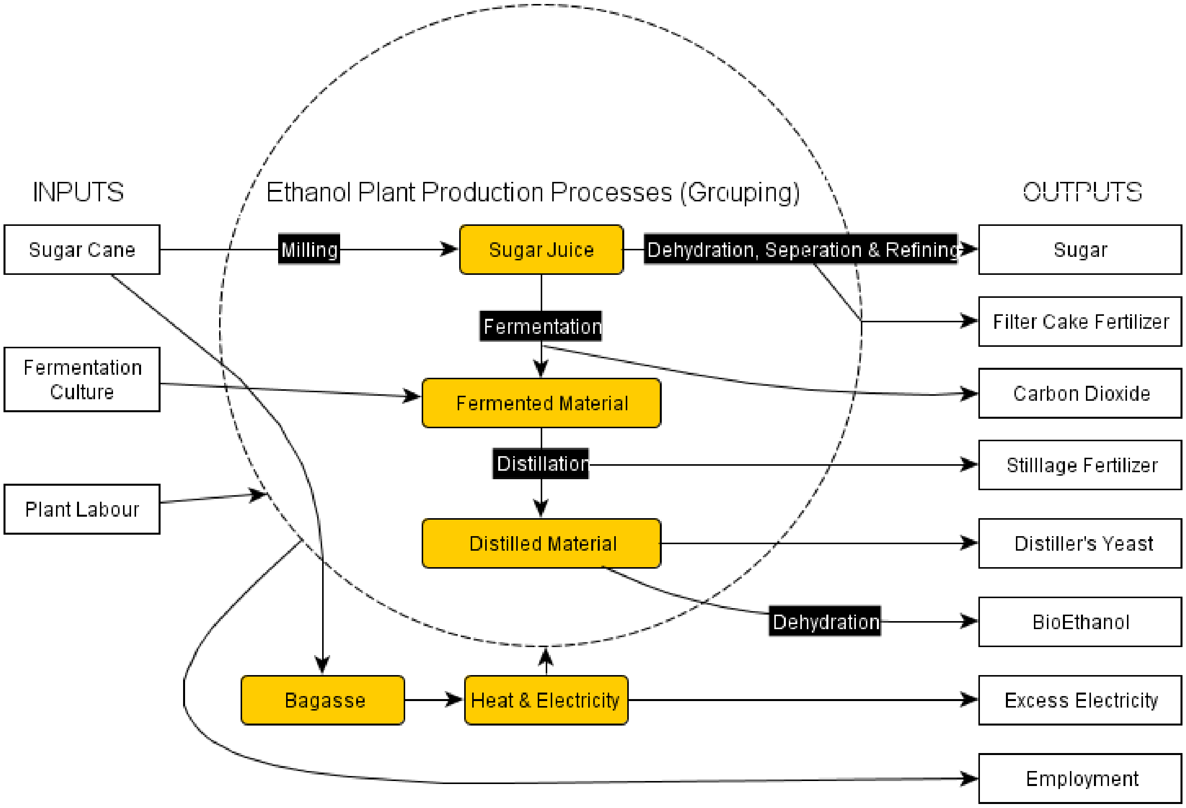


Figure 5. First generation sugarcane bioethanol production chain organized to show the pathway from inputs to outputs. Yellow boxes represent stocks and arrows with black box labels represent flows. Adapted from Vaz Rossel et al. (2006).

Inputs and outputs can be used to guide the financial accounting for the Profit category. All inputs have costs associated with them. Many outputs should have revenue associated with them, or costs, in the example of properly disposing of toxic substances. In this way, it will be possible to estimate operational costs and revenues, and whether a profit can be expected or not. The chain can also be used to account for other quantifiable flows, such as energy.

For the fixed inputs and outputs mentioned above, they mostly pertain to initial costs and effects. As such, they can be used for calculations, such as return on investment, or to consider one off adverse effects of installation.

This exercise centers on the biorefinery, identifying inputs and outputs. For the next step, these can be used to help identify the channels of interaction with the wider environmental, social and economical system of the community.

3.2 - Fuzzy Cognitive Map

Fuzzy Cognitive Maps (FCMs) (Kosko, 1986), like Cognitive Maps (Axelrod, 1976), are graphical system representations with linkages between components representing interaction. Cognitive Maps and FCMs are *directed graphs*, containing *nodes*, or concepts/elements, connected by *edges*, represented as an arrow, implying causal connectivity. The term fuzzy, coming from fuzzy logic (Zadeh, 1965), relates to the casual reasoning used to derive the degree and direction of interaction, such as weakly positive or strongly negative. It allows semi-quantification under uncertainty and hence access to analytical tools from Graph Theory.

The use of FCMs to support decision-making concerning biorefineries was proposed by Lopolito et al. (2011) for the policy level. Specifically, they refer to the uncertainty and complexity of biorefinery systems and their effects on society and the environment. According to Lopolito et al., uncertainty arises from the novelty of biorefineries in rural areas, and the consequent lack of data and certainty on relationships between elements; complexity recognizes the causal and adaptive entanglement of system interactions and the resulting difficulty of describing or modeling.

These challenges are also present in the community level focus of this methodology. Novelty is more accentuated in the developing world where pioneering traces can be found. As for complexity, the People Planet Profit approach to assess this system requires looking at both imprecise and multi-dimensional relationships.

The FCM is relatively simple, not requiring specific expertise, much time/resources, or quantitative data (van Vliet, 2010). By valorizing empirical knowledge, it encourages a wide consultation of stake-holders. It adopts assumptions of complex systems representing a post-normal procedure (Prigogine, 1987; Ramos-Martin, 2003; Funtowicz et al., 1991). Moreover, it offers space for tradeoff recognition and quantification. As such, it is an appropriate and useful tool to judge rural biorefinery development options in developing countries.

The process involved is presented below.

- *3.2.1 Selecting Variables*

The first step in constructing a FCM involves identifying the variables, also called nodes, that will be considered. It is important that these concepts be variable, such as water quality rather than water (Kosko, 1985).

There are multiple ways to derive variables. As mentioned, inputs and outputs from the previous step can be useful to identify how the biorefinery interacts with its surroundings. For example, residues from figure 5 can be returned to farmer's fields affecting soil fertility. Once again, it must be stressed that this is a subjective process that should be adapted to user needs: e.g. N and P leaching into a river can be two separate variables (river N concentration and river P concentration), a single more general one (water quality), or even a consequent effect (severity of eutrophication).

It is necessary that a variable be adopted to represent the biorefinery. This can be directly pertaining to the production process (e.g. production volume) or an important effect of the biorefinery (e.g. Land Under Sugar Plantation from figure 6). Clearly, several variables can also be used to represent the operation of the biorefinery in the larger social and environmental context represented by the FCM.

To derive FCM variables, van Vliet et al. (2010) had stakeholders brainstorm different variables in a workshop setting and agree on a final list. This method is effective as it allows for discussion and interaction between stakeholders, and eventually, the emergence of a consensus. However, it requires bringing stakeholders into the same room. Complications can arise from differences in language and inter-cultural differences of expression and interaction. Alternatively, variable lists can be combined by the researcher after separate consultation with stakeholders and experts.

Çoban et al. (2005) found an exponential decrease in additional variables obtained when increasing amounts of people were consulted. This should be taken into account to encourage more consultancy but with some limit, as resources are required. Seeking a greater diversity of correspondents in regards to expertise or stakeholder position will probably also avoid diminishing marginal returns.

After representative variables are identified, indicator variables for People and Planet can be included to have the FCM track effects on these categories. Indicators developed by UN's Commission on Sustainable Development offer a good reference (UN, 2007). Hass et al. (2002) compiled a large review of national and international indicator sets for sustainability.

Depending on the intentions for final presentation of the process, indicator variables can also be linked to a general People and Planet variable with arrows identifying the effect of the indicators on the composite category. In the case one wishes to focus on and report specific indicator effects, this is not necessary. Alternatively, indicator variables can be left out and the category variables People and Planet can be directly linked to the environmental and social variables.

There are three types of variables usually associated with FCMs (Çoban et al., 2005): senders, transmitters and receivers. Sender variables have arrows directed from them to other variable(s) but no arrows directed from other variables towards them. Transmitters have arrows directed from and to them from other variables. Receivers have arrows directed to them but have none emitting from them.

In the FCM set-up used for this methodology, the sender variable(s) will be the one(s) identified to represent the operation of the biorefinery. The transmitter variables will be social and environmental variables identified by stakeholders. Another category of transmitter variables will be the indicator variables if they are used and connected to final category variables of People and Planet. In the case that they are used by the category variables are not used in the FCM, the indicators will be receiver variables. In the case that People and Planet are used but not indicators, as in example figure 6, People and Planet will be the receiver variables.

- *3.2.2 Drawing the FCM*

The second step is to draw the cognitive map. Variables are represented as rectangles on a paper or sticky notes on a poster, with arrows connecting them demonstrating effect. Ideally, this would require stakeholder or expert consultation and discussion to avoid bias and overlooking relationships. van Vliet et al. (2010) conducted this in a workshop setting.

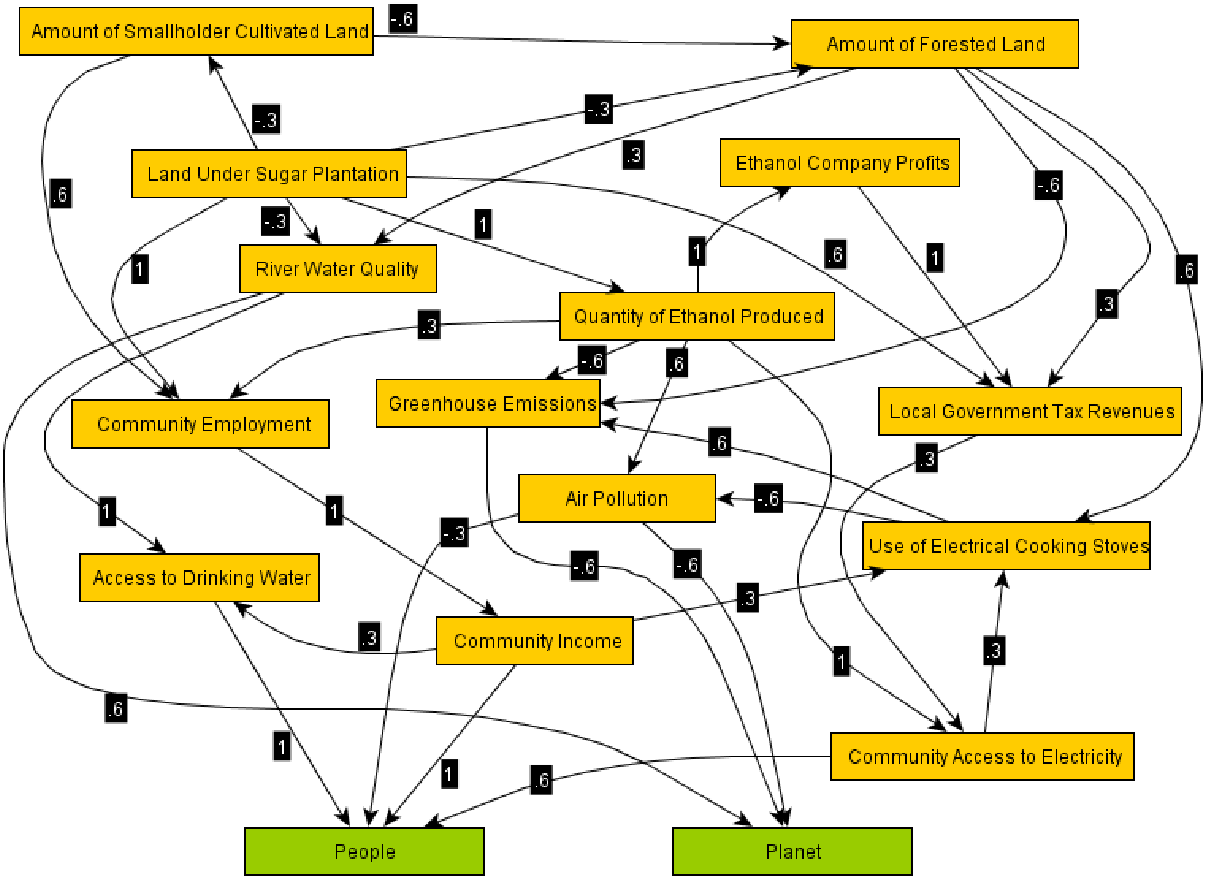


Figure 6. An example Fuzzy Cognitive Map of the effects of a bioethanol plant on the local community. Boxes are variables, or nodes, and arrows are directed causal relationships, or edges, with the value representing the weighed strength. No cycles are present.

After the graphical structure is obtained, the next step would be to rank the strength of the relationships. Several approaches can be adopted for this exercise. van Vliet et al. (2007) used four qualitative categories (++, +, -, --) indicating strong positive, positive, negative and strong negative effects. Positive means a direct relationship between variables, an increase in one results in an increase in the other; negative means an indirect relationship between variables, an increase in one results in a decrease in the other. Kok (2009) used a more nuanced classification: Strong-Strong, Strong-Medium, Strong-Weak, Medium-Strong, Medium-Medium, Weak-Strong, Weak-Medium, Weak-Weak for both positive and negative. Kok's method entailed asking respondents to classify effects into Strong-Medium-Weak, and then to reclassify each group into Strong-Medium-Weak. Fuzzy strengths can be obtained from known knowledge, expert opinion, combining stake-holder and expert opinion, or the workshop approach.

Next, these fuzzy categories are translated into values between 0 and 1. van Vliet et al. (2010) used 1, .5, -.5 and -1 for the aforementioned categories. Kok (2009) used .2, .3, (…) .9, both negative and positive.

It is important to consider time scales when constructing the FCM. To do this, the strength of relationships should be framed in a set time step (e.g. 1 year). Whether these effects strengthen or weaken overtime should also be established. Kok (2009) included feedback mechanisms for variables. If these are not equal to 1, it would mean that the effects of the variable are changing over time.

- *3.2.3 Adjacency Matrix*

After the semi-quantification has been conducted, the interactions of the FCM can be summarized with an adjacency matrix. An example adjacency matrix is shown in figure 7 corresponding to the FCM of figure 6. This involves making a matrix, or table, with each variable occupying a row and a column. The interactions from the FCM are translated into the graph with relationships from row variables on the column variables. From this, senders, receivers and transmitters can be identified; although the indicators should always be the receivers. Senders should be the biorefinery system and related coproduction if it was not included in the flow chart.

$$\begin{array}{lr|cccccccc|}
 & \textbf{on:} & x_1 & x_2 & x_3 & x_4 & x_5 & (\ldots) & x_{15} & x_{16} \\
\hline
 & \mathit{Land\,Under\ Sugar\ Plantation}(x_1) & 0 & -.3 & -.3 & 1 & 0 & (\ldots) & 0 & 0 \\
 & \mathit{Amount\ of\ Smallholder\ Cultivated\ Land}(x_2) & 0 & 0 & 0 & .6 & 0 & (\ldots) & 0 & 0 \\
 & \mathit{River\ Water\ Quality}(x_3) & 0 & 0 & 0 & 0 & 1 & (\ldots) & 0 & 0 \\
\textbf{effect of:} & \mathit{Community\ Employment}(x_4) & 0 & 0 & 0 & 0 & 0 & (\ldots) & 0 & 0 \\
 & \mathit{Access\ to\ Drinking\,Water}(x_5) & 0 & 0 & 0 & 0 & 0 & (\ldots) & 1 & 0 \\
 & (\ldots) & (\ldots) & (\ldots) & (\ldots) & (\ldots) & (\ldots) & (\ldots) & (\ldots) & (\ldots) \\
 & \mathit{People}(x_{15}) & 0 & 0 & 0 & 0 & 0 & (\ldots) & 0 & 0 \\
 & \mathit{Planet}(x_{16}) & 0 & 0 & 0 & 0 & 0 & (\ldots) & 0 & 0 \\
\hline
\end{array}$$

Figure 7. An adjacency matrix of the fuzzy cognitive map in figure 6. The values in the matrix show the effect of a row variable on a column variable; that is, the -.3 first row second column is the effect of Land Under Sugar Plantation on Amount of Smallholder Cultivated Land. Variables are labeled x_1 to x_{16} and are the same for rows and columns. (…) signifies continuation of the matrix for variables not included in the image, namely x_5 to x_{14}.

- *3.2.4 Running FCM Iterations*

Using the adjacency matrix, the FCM can be run through iterations to see the effect of the biorefinery on the indicators or People and Planet categories. As the matrix values represent relationship strengths and directions, their multiplication with state variables will demonstrate model indications of long-term changes of the social-environmental system resulting from the biorefinery option selected. As the FCM is semi-quantitative in input and method, the state variables for all the variables in the FCM need not have any value besides 0; their change through the iterations will demonstrate direction and relative magnitude of biorefinery changes. The set of state variables is combined into a change vector in a single row as in figure 8. The multiplication of the initial (all zero) state variable with the adjacency matrix is an iteration. The multiplication of the resulting change vector with the adjacency matrix is the second iteration, and so on.

$$\begin{bmatrix} S_1 & S_2 & S_3 & S_4 & S_5 & (\ldots) & S_{13} & S_{14} & S_{15} & S_{16} \end{bmatrix}$$

Figure 8. An example change vector pertaining to figure 6. S = state value. (…) = variables not included between S_5 and S_{13}.

To conduct iterations, the following modifications must be made (pers. comm.: Kok):

- An “outside driver” must be selected. For this methodology, this will be the sender variable(s) pertaining to the biorefinery operation.
- The outside driver will receive a value in the change vector that is non-zero. This can be any value, .1 was used for the example iterations (figure 9).

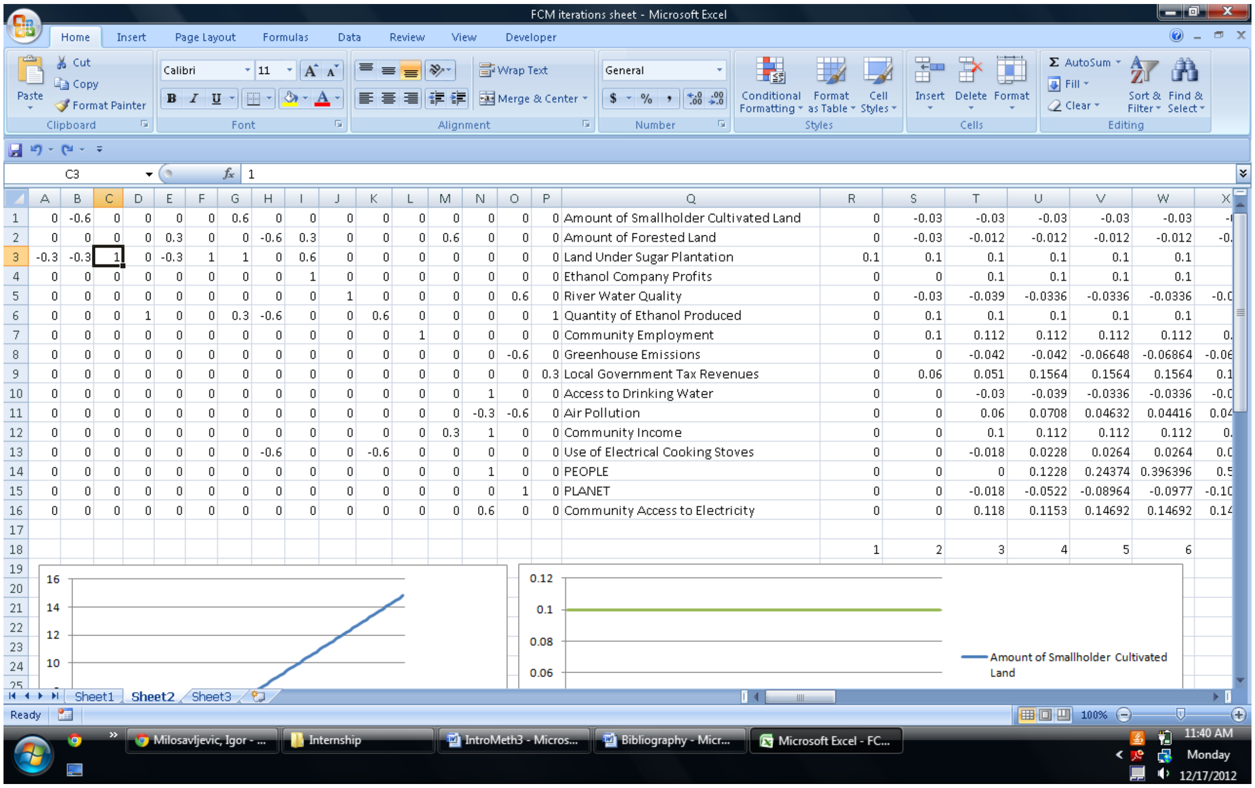
- The adjacency matrix has to be altered. A value must be assigned to the effect of the "outside driver" on itself, on the FCM represented as an arrow to itself. For the example, 1 was used (see effect of x_3 on x_3 in figure 9, the cell is selected).

As mentioned before, it is important to keep the time dimension of the effects as equal as possible when defining edge strength.

- *3.2.5 Using Excel*

The arithmetic of iterations is simple and can be done by hand, but it is easier to use a computer. The example FCM has 16 variables with a 16*16 adjacency matrix resulting in 256 arithmetic operations for every iteration. Since one wishes to see the FCM system at stability, at least 20 iterations should be conducted. When multiple biorefinery options are explored, this will have to be conducted for each option.

Excel can make this process easier. The adjacency matrix from figure 7 is shown as a screenshot from excel in figure 9 (cells A1 to P16) with the aforementioned modifications already conducted.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
1	0	-0.6	0	0	0	0	0.6	0	0	0	0	0	0	0	0	0	Amount of Smallholder Cultivated Land	0	-0.03	-0.03	-0.03	-0.03	-0.03
2	0	0	0	0	0.3	0	0	-0.6	0.3	0	0	0	0.6	0	0	0	Amount of Forested Land	0	-0.03	-0.012	-0.012	-0.012	-0.012
3	-0.3	-0.3	1	0	-0.3	1	1	0	0.6	0	0	0	0	0	0	0	Land Under Sugar Plantation	0.1	0.1	0.1	0.1	0.1	0.1
4	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	Ethanol Company Profits	0	0	0.1	0.1	0.1	0.1
5	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.6	0	River Water Quality	0	-0.03	-0.039	-0.0336	-0.0336	-0.0336
6	0	0	0	1	0	0	0.3	-0.6	0	0	0.6	0	0	0	0	1	Quantity of Ethanol Produced	0	0.1	0.1	0.1	0.1	0.1
7	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	Community Employment	0	0.1	0.112	0.112	0.112	0.112
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.6	0	Greenhouse Emissions	0	0	-0.042	-0.042	-0.06648	-0.06864
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	Local Government Tax Revenues	0	0.06	0.051	0.1564	0.1564	0.1564
10	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	Access to Drinking Water	0	0	-0.03	-0.039	-0.0336	-0.0336
11	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.3	-0.6	0	Air Pollution	0	0	0.06	0.0708	0.04632	0.04416
12	0	0	0	0	0	0	0	0	0	0	0	0	0.3	1	0	0	Community Income	0	0	0.1	0.112	0.112	0.112
13	0	0	0	0	0	0	0	-0.6	0	0	-0.6	0	0	0	0	0	Use of Electrical Cooking Stoves	0	0	-0.018	0.0228	0.0264	0.0264
14	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	PEOPLE	0	0	0	0.1228	0.24374	0.396396
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	PLANET	0	0	-0.018	-0.0522	-0.08964	-0.0977
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0	0	Community Access to Electricity	0	0	0.118	0.1153	0.14692	0.14692
17																							
18																		1	2	3	4	5	6

Figure 9. A screenshot of excel being used to conduct FCM iterations. Cells A1 to P16 are an adjacency matrix from figure 7 with the modifications specified in *Running FCM Iterations* conducted. Column Q shows the names of the variables and their order (e.g. x_1, x_2, x_3, … x_{16}). Column R is the original change vector with the state value of Land Under Sugar Plantation changed from 0. The successive columns are results from iterations.

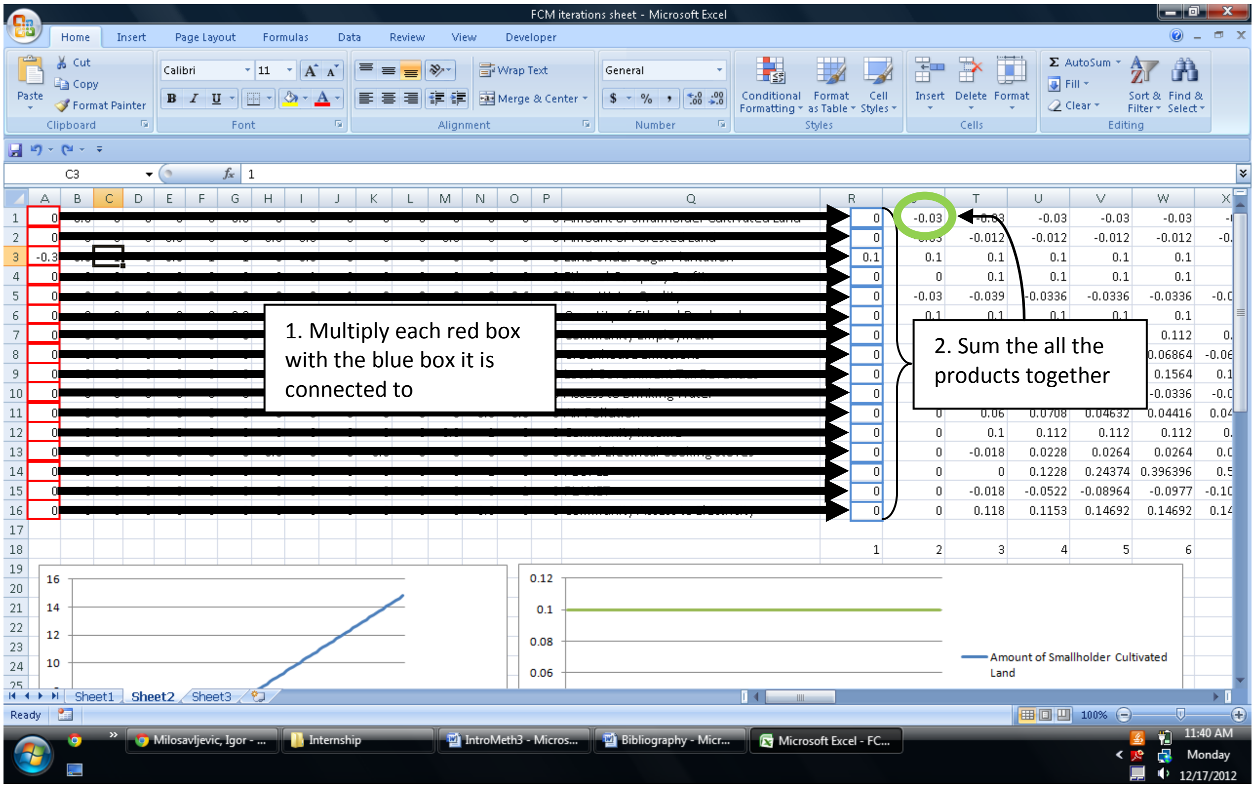
Notice that the initial change vector in column R of figure 9 is inverted (columns and rows are opposite) compared to figure 8. This was done for ease of operation in excel. The initial change vector is specified by the user; e.g. all zeros except for the "outside driver". Table 1 shows the formulas for each cell used to calculate the next change vector (column S in figure 10). Each new value of x_1 in the change vector come from multiplying the effect of all variables on x_1 with their state values and summing it up.

Table 1. The formulas entered in column S from figure 9 to conduct the first iteration.

Cell	Formula Entered
S1	=$A1*R$1+$A2*R$2+$A3*R$3+$A4*R$4+$A5*R$5+$A6*R$6+$A7*R$7+$A8*R$8+$A9*R$9+$A10*R$10+$A11*R$11+$A12*R$12+$A13*R$13+$A14*R$14+$A15*R$15+$A16*R$16
S2	=$B1*R$1+$B2*R$2+$B3*R$3+$B4*R$4+$B5*R$5+$B6*R$6+$B7*R$7+$B8*R$8+$B9*R$9+$B10*R$10+$B11*R$11+$B12*R$12+$B13*R$13+$B14*R$14+$B15*R$15+$B16*R$16
S3	=$C1*R$1+$C2*R$2+$C3*R$3+$C4*R$4+$C5*R$5+$C6*R$6+$C7*R$7+$C8*R$8+$C9*R$9+$C10*R$10+$C11*R$11+$C12*R$12+$C13*R$13+$C14*R$14+$C15*R$15+$C16*R$16
S4	=$D1*R$1+$D2*R$2+$D3*R$3+$D4*R$4+$D5*R$5+$D6*R$6+$D7*R$7+$D8*R$8+$D9*R$9+$D10*R$10+$D11*R$11+$D12*R$12+$D13*R$13+$D14*R$14+$D15*R$15+$D16*R$16
S5	=$E1*R$1+$E2*R$2+$E3*R$3+$E4*R$4+$E5*R$5+$E6*R$6+$E7*R$7+$E8*R$8+$E9*R$9+$E10*R$10+$E11*R$11+$E12*R$12+$E13*R$13+$E14*R$14+$E15*R$15+$E16*R$16
S6	=$F1*R$1+$F2*R$2+$F3*R$3+$F4*R$4+$F5*R$5+$F6*R$6+$F7*R$7+$F8*R$8+$F9*R$9+$F10*R$10+$F11*R$11+$F12*R$12+$F13*R$13+$F14*R$14+$F15*R$15+$F16*R$16
S7	=$G1*R$1+$G2*R$2+$G3*R$3+$G4*R$4+$G5*R$5+$G6*R$6+$G7*R$7+$G8*R$8+$G9*R$9+$G10*R$10+$G11*R$11+$G12*R$12+$G13*R$13+$G14*R$14+$G15*R$15+$G16*R$16
S8	=$H1*R$1+$H2*R$2+$H3*R$3+$H4*R$4+$H5*R$5+$H6*R$6+$H7*R$7+$H8*R$8+$H9*R$9+$H10*R$10+$H11*R$11+$H12*R$12+$H13*R$13+$H14*R$14+$H15*R$15+$H16*R$16
S9	=$I1*R$1+$I2*R$2+$I3*R$3+$I4*R$4+$I5*R$5+$I6*R$6+$I7*R$7+$I8*R$8+$I9*R$9+$I10*R$10+$I11*R$11+$I12*R$12+$I13*R$13+$I14*R$14+$I15*R$15+$I16*R$16
S10	=$J1*R$1+$J2*R$2+$J3*R$3+$J4*R$4+$J5*R$5+$J6*R$6+$J7*R$7+$J8*R$8+$J9*R$9+$J10*R$10+$J11*R$11+$J12*R$12+$J13*R$13+$J14*R$14+$J15*R$15+$J16*R$16
S11	=$K1*R$1+$K2*R$2+$K3*R$3+$K4*R$4+$K5*R$5+$K6*R$6+$K7*R$7+$K8*R$8+$K9*R$9+$K10*R$10+$K11*R$11+$K12*R$12+$K13*R$13+$K14*R$14+$K15*R$15+$K16*R$16
S12	=$L1*R$1+$L2*R$2+$L3*R$3+$L4*R$4+$L5*R$5+$L6*R$6+$L7*R$7+$L8*R$8+$L9*R$9+$L10*R$10+$L11*R$11+$L12*R$12+$L13*R$13+$L14*R$14+$L15*R$15+$L16*R$16
S13	=$M1*R$1+$M2*R$2+$M3*R$3+$M4*R$4+$M5*R$5+$M6*R$6+$M7*R$7+$M8*R$8+$M9*R$9+$M10*R$10+$M11*R$11+$M12*R$12+$M13*R$13+$M14*R$14+$M15*R$15+$M16*R$16
S14	=$N1*R$1+$N2*R$2+$N3*R$3+$N4*R$4+$N5*R$5+$N6*R$6+$N7*R$7+$N8*R$8+$N9*R$9+$N10*R$10+$N11*R$11+$N12*R$12+$N13*R$13+$N14*R$14+$N15*R$15+$N16*R$16
S15	=$O1*R$1+$O2*R$2+$O3*R$3+$O4*R$4+$O5*R$5+$O6*R$6+$O7*R$7+$O8*R$8+$O9*R$9+$O10*R$10+$O11*R$11+$O12*R$12+$O13*R$13+$O14*R$14+$O15*R$15+$O16*R$16
S16	=$P1*R$1+$P2*R$2+$P3*R$3+$P4*R$4+$P5*R$5+$P6*R$6+$P7*R$7+$P8*R$8+$P9*R$9+$P10*R$10+$P11*R$11+$P12*R$12+$P13*R$13+$P14*R$14+$P15*R$15+$P16*R$16

In step 1, each state variable is multiplied with the effect of all the variables on x_1, shown in column A. In step 2, the resulting products are summed up to the new value (circled in green) for the new change vector. For the new state value of x_2 in the first iteration, the effect of all variables on x_2 is multiplied with their respective state variables; all the resulting products are summed up. In a visual representation, the red squares would shift over to column B, and the green circle would drop down to cell S2. This process is used to calculate all the new state values of the new change vector resulting from an iteration.

After the first iteration is conducted, the rest of the iterations can be done by selecting the change vector from the first iteration, S1 to S16. This can be done by clicking on S1 and, holding the mouse down, scrolling down with the cursor over S16. It can also be done by selecting S1, and holding shift pressing the down arrow 15 times until S1 to S16 is selected. Next, place the cursor is the bottom right corner of the selection rectangle where a small black square is located. Scrolling over this square will change the appearance of the cursor from a thick white cross to a thin black cross. Left click and hold, and drag the selection rectangle right, maintaining the same amount of rows being selected. Each additional column represents an additional iteration.



1. Multiply each red box with the blue box it is connected to

2. Sum the all the products together

	R	S	T	U	V	W
1	0	-0.03	[illegible]	-0.03	-0.03	-0.03
2	0	[illegible]	-0.012	-0.012	-0.012	-0.012
3	0.1	0.1	0.1	0.1	0.1	0.1
4	0	0	0.1	0.1	0.1	0.1
5	0	-0.03	-0.039	-0.0336	-0.0336	-0.0336
6	0	0.1	0.1	0.1	0.1	0.1
7	0	[illegible]	[illegible]	[illegible]	[illegible]	0.112
8	0	[illegible]	[illegible]	[illegible]	[illegible]	0.06864
9	0	[illegible]	[illegible]	[illegible]	[illegible]	0.1564
10	0	[illegible]	[illegible]	[illegible]	[illegible]	-0.0336
11	0	0	0.06	0.0708	0.04632	0.04416
12	0	0	0.1	0.112	0.112	0.112
13	0	0	-0.018	0.0228	0.0264	0.0264
14	0	0	0	0.1228	0.24374	0.396396
15	0	0	-0.018	-0.0522	-0.08964	-0.0977
16	0	0	0.118	0.1153	0.14692	0.14692
17						
18	1	2	3	4	5	6

Figure 10. A visualization of an iteration calculations for the state value of x_1 the first iteration. See text.

- *3.2.5 Structural Analysis Options*

Graph theory offers numerous ways to analyze flow charts like the FCM. Below are a few selected examples that are deemed useful for the intended practitioners of this methodology.

Comparing impact of different variables on a given one

The effect of different variables on a given variable can be compared using fuzzy causal algebra (Kosko, 1986). Referring to figure 6, a development agency wishing to improve the social aspects in this system (People) could wonder whether to initiate a management training program to increase Ethanol Company Profits or entrepreneurship training program targeting Community Employment. To do this, all paths between two variables must first be identified; shown in figure 11.

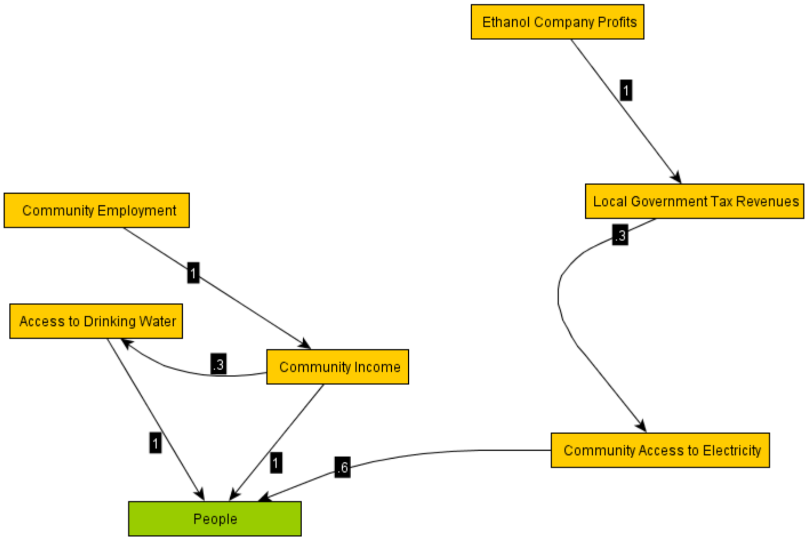


Figure 11. Effects of Ethanol Company Profits and Community Employment on People from figure 6.

Then, for each path, the edges between all the variables must be multiplied together; if this value is greater than one, one is kept:

- Community Employment
  - Pathway 1: Community Employment-Community Income-People
    - 1*1 = 1 -> **1**
  - Pathway 2: Community Employment-Community Income-Access to Drinking Water-People
    - 1*.3*1 = .3 -> **.3**
- Ethanol Company Profits
  - Pathway 1: Ethanol Company Profits-Local Government Tax Revenue-Community Access to Electricity
    - 1*.3*.6 = .18 -> **.18**

Then, all the sums of all the pathways between the two variables are added to each other; if this value is greater one, one is kept.

- Community Employment
  - Pathway 1 + Pathway 2: 1 + .3 = 1.3 -> **1** (bounded sum can be 1 max, -1 min)
- Ethanol Company Profits
  - Pathway 1: .18 -> **.18**

This can be very useful to compare effects between different variables on a variable of interest. Targeting Community Employment over Ethanol Company Profits will be more instrumental to improve the social conditions of the community according to the FCM from figure 6.

This process is represented in the equation below as provided by Wellman (1994) for non-cyclical FCMs*:

* Cycles in FCMs signify interactions between at least 3 variables that form a loop; that is, variable one affects variable two, which affects variable three, which in turn affects variable one.

$$\bigoplus_{p \in P_{a,b}} \left(\bigotimes_{(c,c',\delta) \in p} \delta \right)$$

Where: $P_{a,b}$ = set of paths in cognitive map from node *a* to node *b*
p = a given path part of set *P*
c = node on path *p*
c’ = successive node on path p
δ = strength weight of node c on node c’

The strength of a single variables effects

Lopolito et al. (2011) show indices that can be used to calculate the relationship a variable has on the variables it is connected to. These calculation are shown in table 2.

Table 2. Punctual indices for structural analysis from Lopolito et al. (2011).

Index	Formulation	Description
In-Degree (iDv_i)	$iDv_i = \sum_{K=1}^{N} a_{ki}$	The in-degree shows the cumulative strength of connections entering the variable *I* and coming from other variables *k*, a_{ik}. *N* is the number of variables.
Out-Degree (iOv_i)	$iOv_i = \sum_{K=1}^{N} a_{ik}$	The out-degree shows the cumulative strength of connections exiting from the variable *I* and reaching the other variables *k*, a_{ki}. *N* is the number of variables.
Centrality/total degree (C_i)	$C_i = iDv_i + iOv_i$	Centrality describes the contribution of a variable in a cognitive map by showing how a variable is connected to others and the cumulative strength of these links. This index is calculated as the sum of the in-degree and out-degree indices.

As an example, the iDv_i iOv_i and C_i of Use of Electrical Cooking Stoves from figure 6 will be calculated:

- iDv_i – cumulative strength of effects on Use of Electrical Cooking Stoves from other variables
    - Other Variables: Community Access to Electricity, Amount of Forested Land, Community Income
    - Calculation: .3 + .6 + .3 = 1.2
- iOv_i – cumulative strength of effects from Use of Electrical Cooking Stoves onto other variables
    - Other Variables: Greenhouse Emissions, Air Pollution
    - Calculation: -.6 + -.6 = -1.2
- C_i – overall cumulative strength of variable in FCM
    - Calculation: 1.2 + -1.2 = 0

A simple way to derive these values is to use the adjacency matrix. Row values represent strength of effects on other values; columns values represent strength of effect onto the variable. The sum of all row values for a variable is hence the out-degree; the sum of all column values is the out-degree. This shorthand is useful if one would like to compare all the variables.

- *3.2.6 Interpretation and Presentation of Results*

Interpretation should be relative as the FCM method is semi-quantitative. Referring to figure 12, the final value of Local Government Tax Revenues cannot be said to be twice that of Community Employment, it should be said that the model implies a stronger effect of the biorefinery on Local Government Tax Revenues than Community Employment by relatively twice. Close values such as Quantity of Ethanol Produced and Community Income cannot be said to be different. The relative and semi-quantitative construct of the FCM method must be taken into account when interpreting results. They cannot be absolute as is the case with quantitative methods.

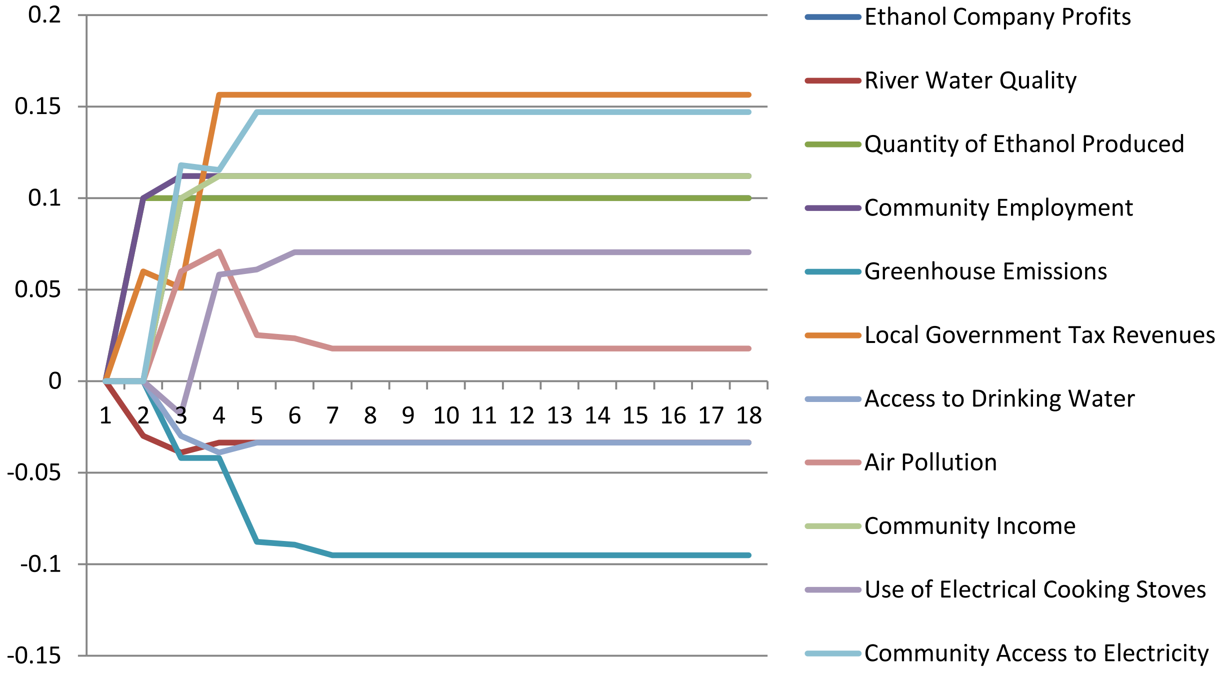


Figure 12. State values of transmitter variables for 18 iterations. Stability of the system is reached.

Presentation will depend on the FCM set-up and what the practitioner desires to present.

It is important to realize that the state values of sender, transmitter and receiver variables have different behavior in the iterations. The state variable of sender variables does not change, as it lacks an incoming effect from another variable. Transmitter variables change in the first dozen iterations or so and stabilize at a constant value. Receiver variables stabilize with a slope (tilted, not flat), in contrast to transmitter variables; see figure 13 compared to figure 12.

As such, transmitter variables can have their long-term iteration values presented intersects. Receiver variables can have their slopes presented as a measure of impact. The implications are similar to using intersects as long as the presentation of the results discerns between the two since slopes will doubtlessly tend to be significantly smaller on average. The same method and receiver variables should be used for all the options being explored to allow for comparison.

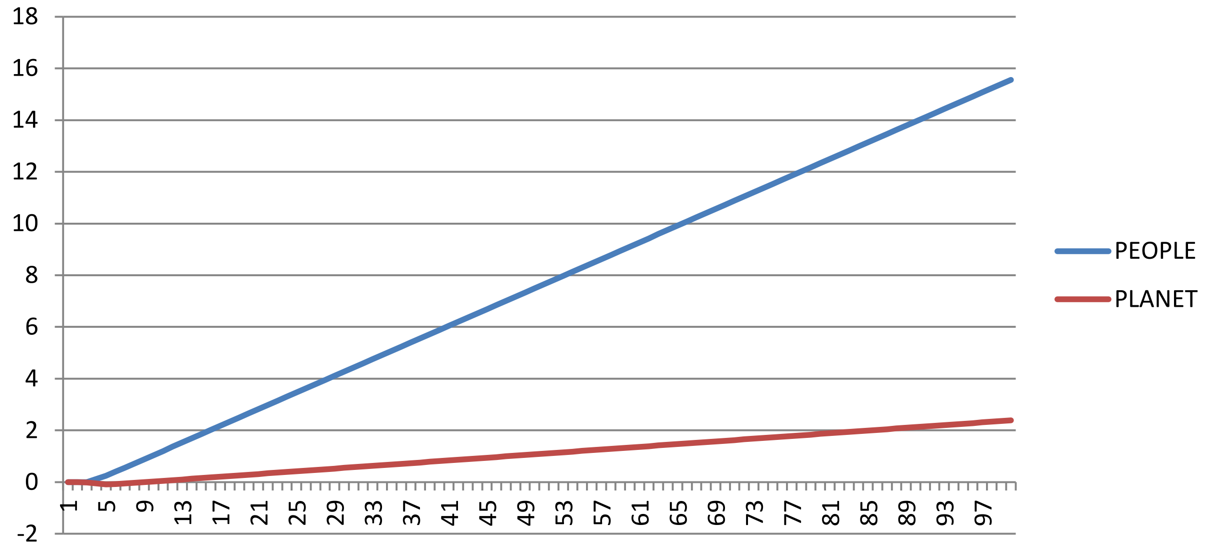


Figure 13. State values of receiver variables for 100 iterations. Stability of the system is reached.

The presentation of data will depend in large part to what is desired to be presented. The line graphs in figure 12 and 13 are technical and can be misinterpreted by readers not familiar with the semi-quantitative nature of the methodology. As such, final values of indicators or the category variables should be used. The spider diagram offers a good visual option which shows the People Planet Profit scores of each option. It can either show only these three variables, or indicators that belong in these categories. It allows for easy comparison between the score achievements of each option being employed. An example is shown in figure 14 and figure 15.

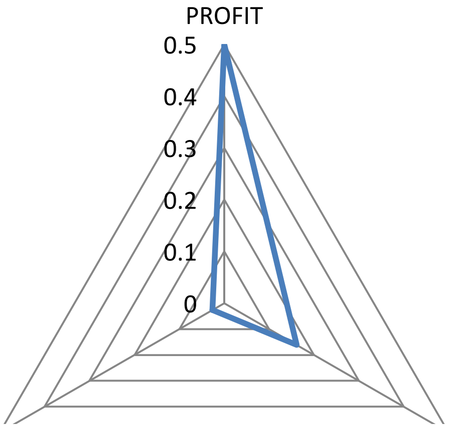


Figure 14. Example People-Planet-Profit pyramid. Planet and Profit values come from the slope of figure 13. Profit was set at .5.

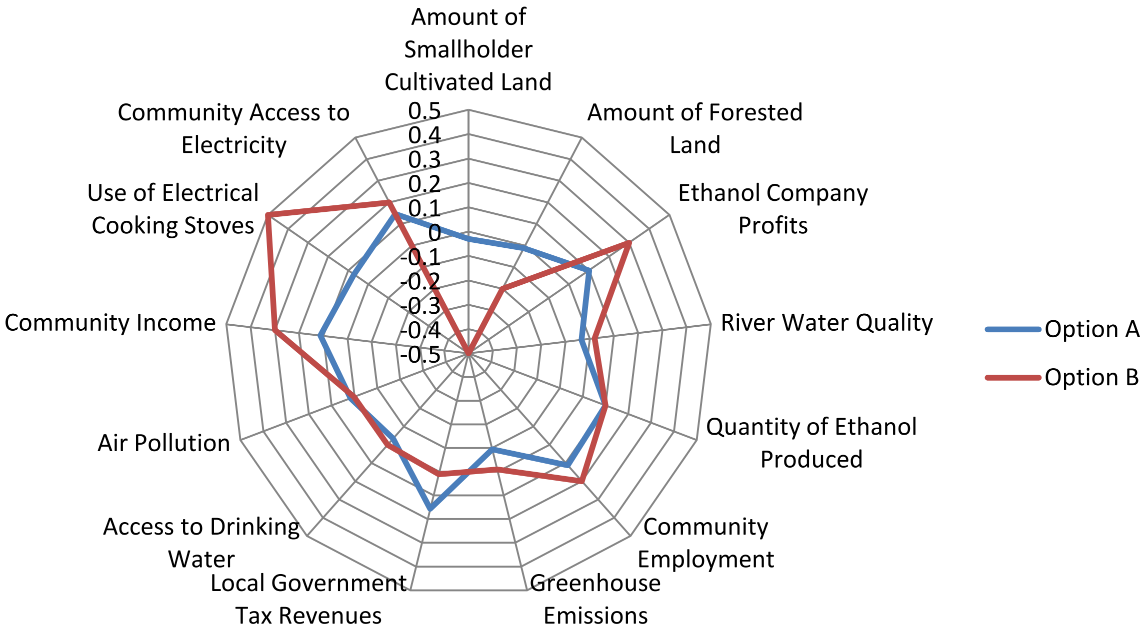


Figure 15. Example spider diagram for indicators from example used in text. Option A comes from indicator results obtained from the practice iteration, shown in figure 12. Option B is random for visual demonstration.

4 - Reflection on Methodology

4.1 – Methodology Strengths

The methodology leads a structured cognitive process to develop and judge biorefinery options in a bioenergy production chain, valorizing and channeling expert opinion to allow for some degree of causative semi-quantitive analysis. It is not demanding in terms of cost or resources, and its practice can be propagated without the requirement for extensive technical knowledge. As a contrast, no other methodology for judging sustainability is able to fulfill the critical requirement of a lack of data amidst great uncertainty (section 2.4).

The flow-chart is a flexible visual process that maps production chains. It allows for exploration of available options by identifying intermediary products and outputs; these can be diverted to alternative processing options. The flow chart offers a guide to calculate Profit perspectives of different options and, allows for early elimination of unreasonable options.

FCM organizes and channels expert opinion to construct an interpretation of what is expected to happen within a wider context. It presents analytic tools for identification of critical elements in a system and to compare effects between different variables. The advantages of FCM over other semi-quantitative methods are listed by van Vliet (2010):

- It is not difficult to understand
- It is not difficult to teach partners
- Has a high level of integration as its quality is contingent on a wide consultation
- Can be performed in a short time
- Gives a system description

Fuzzy Cognitive Mapping is inherently an inclusive process that allows for identification of stakeholder position and interest as it relates to potential development of biorefineries. The draws on and combines expert and local knowledge and combines it into an analyzable structure. In comparison, expert opinion is unavoidably selective, does not achieve the same degree of holistic representation of reality and conclusions are based on unstructured intuition. The reliance on stakeholders also dilutes the personal bias of the user of the methodology.

4.2 – Methodology Drawbacks

In general, the methodology is quick and dirty. In this way, its level of precision is low. Results have to be viewed with much caution, taking note of specific actions conducted throughout the methodology. As such, the final headline scores can be misleading requiring observers to be familiar with the cautions and process of the methodology itself, and how it was applied in a specific case.

The flow chart and accounting method is simplistic and projects an ideal situation. Everything in the production chain is assumed to work as projected by the user of the methodology, not accounting or allowing for mishaps, malfunctions, failures, and underperformance of technical options; challenges that will no doubt impact financial considerations considerably. As such, it is heavily dependent on user judgment to determine technical feasibility. In the case of novel technologies, particularly under previously untested conditions (e.g. climate), the degree of uncertainty of technical performance can be very large. Costs are assumed to be constant, making the projection valid for only in the short-term.

FCM depends on how the user applies the methodology. Instructions give a direction but do not draw out a specific path. As such, experience with the methodology will impact results to a large degree. Other elements dependent on the user’s application of the methodology will impact results greatly: the number of people interviewed (Çoban et al., 2005), the perception of the user by the stakeholders consulted, the user’s choice of stakeholders, and communicative ability of the user himself or herself. The FCM method is vulnerable to many factors which make its exact replicability impossible, an undesirable characteristic of a scientific methodology. There is no opportunity for validation of results.

The results from the FCM are themselves fuzzy, and hence relative. In consequence, conclusions drawn are also fuzzy and do not allow for clear cut comparison and hence choices between options.

The methodology is not rigid. The reason for this flexibility is to allow it to mold to the needs of the user in the situation. However, this also means that results between locations cannot be compared and that the user will have to present his steps in a transparent manner.

van Vliet (2010) organized two parallel workshops to address the same issue with FCMs. The results yielded different stable system values for variables examined, as can be expected. Significantly, some variables found themselves increased in one group and decreased in the other. Hence, the fuzziness of the final numbers presented as headline scores are still counter intuitive to an scientific culture expecting certainty to a large degree.

5 - Conclusion

The methodology presented in this work guides a cognitive process of biorefinery possibilities in a bioenergy production chain. It examines People, Planet and Profit effects of different proposals and provides a method to judge between them. Due to its simplicity and low demand, it can be applied for rural communities in developing countries.

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