

CHAPTER 1: INTRODUCTION

1.1 What are Biofuels?

A biofuel is a liquid or gaseous fuel that is derived from biomass (Demibras, 2008). Biofuels can be produced in a variety of ways and can be classified in terms of conventional and advanced biofuels. Conventional biofuels include bio-ethanol and bio-diesel produced from traditional agricultural crops by established technologies. Advanced biofuels include second generation bio-ethanol and synthetic diesel produced from lignocellulosic biomass by developing technologies. The simplest (conventional) method for the manufacture of biodiesel is a chemical transesterification process by which oils and fats are converted into fatty acid methyl ester (FAME). Most commercial production of biodiesel is based on vegetable oils such as palm oil, canola oil and soybeans. Bio-ethanol can be produced from any agricultural feedstock containing high concentrations of sugar or starch by fermentation, distillation and bio-ethanol purification. Common feedstocks used for the production of bio-ethanol include sugarcane, sugarbeet, sorghum and rye.

Bio-ethanol and bio-diesel are increasingly being promoted as viable substitutes for conventional fossil fuels. They are compatible with current infrastructure and vehicle technology and have potential for fast introduction on a commercial scale. They are preferably used in low-percentage blends with conventional fuels because such blends do not require any modification in the present engines.

Biofuels have been championed as an energy source that ensures energy security, reduces vehicle emissions and provides a new source of income to farmers. Following

Brazil's footsteps, many countries have launched new programme to encourage production and use of biofuels. However, the claims of the potential benefits are now being contested (Malhi et al., 2008). Conventional biofuels are increasingly being regarded as a cause of deforestation and a threat to food security, thereby raising questions about their sustainability and viability (Doornbosch and Steenbilk, 2008).

1.2 Relevance of Biofuels to Sustainability

Biofuels are very efficient in lowering emissions of harmful pollutants, decreasing greenhouse gases and promoting other environmental advantages. Moreover, they also ensure increased energy security, decreased dependence on oil imports and increased employment. For instance, the sugarcane industry is the largest agro-based industry in India and it also happens to be the core of ethanol production. It employs around 45 million farmers that comprise almost 7.5% of the rural population (Gonsalves, 2002).

Sweet sorghum is cultivated on over 29 million hectares of cultivable land in India. On an average, 1160 kg/ha of yield is obtained. Sugar cane, which is cultivated on relatively much smaller area, i.e. 4 million hectares, accounts for a yield of 65,000 kg/ha that is greater than sweet sorghum. Sugar cane is the highest yielding crop used as biofuel in India. In India, the sugarcane molasses are fermented to form ethanol, an excellent biofuel which can be easily blended with petrol. Ethanol is gaining worldwide acceptance in the transportation sector. At the same time, biodiesel is being produced from *Jatropha*.

In their study, Gerbens-Leenes et al.(2008), reported that the Water Footprint of bioethanol was less than that of biodiesel. For generating electricity from the bio-crops, it was found that maize and sugar cane were the most favourable crops whereas soybean and rapeseed were most favourable for producing biodiesel.

While production of biofuels can potentially decrease the dependence on oil imports and ensure energy security, it can also lead to improved social well being especially in the rural areas of developing countries by providing rural employment, increasing the income of the farmers and permitting increased access to energy supplies.

1.3 Can Biofuels be Sustainable?

According to the Brundtland Commission of the United Nations (UN, 1987), sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their needs. As an extension of this, sustainability requires reconciliation of environmental, economic and social demands. Applying the concept of sustainability to biofuels, we must ensure that in order to be a viable alternative to fossil fuels, a biofuel should be able to provide net energy gain, have environmental benefits, be economically competitive and be producible in large quantities without reducing food supplies (Hill et al., 2006). The relative importance of the different environmental, economic and social facets of biofuel production varies depending on the specific biofuel crop being considered. Hence, the selection of a suitable biofuel requires a framework that allows different alternatives (such as biofuel crop options) to be consistently evaluated and compared (Robertson et al. 2008). The numerous stakeholders, such as farmers, engineers, economists, policy makers, and government agencies, have

different objectives, goals, criteria and viewpoints which too need to be reconciled (Phdungslip, 2009). Biofuel systems are complex, develop at different scales and involve a number of different market segments, supply chains, and stakeholders with different priorities and objectives that must be reconciled. This makes decision making pertaining to biofuel sustainability a slow, complex and difficult process as divergent views and interests of various stakeholders have to be taken into account before a final decision is made. Further, sustainability related decision making cannot be treated solely as an expert analysis; it necessarily needs to involve all the stakeholders and their varying perspectives (Elghali et al, 2007).

1.4 Sustainability Related Decision Making

Reconciling conflicting objectives and stakeholder priorities lies at the heart of sustainability related decision making. In order to provide support for sustainability related issues like biofuel production, a framework is needed which reconciles stakeholder viewpoints with quantitative data pertaining to various sustainability criteria. Such a framework is provided by Multi Criteria Decision Making (MCDM) in the form of Analytical Hierarchy Process (AHP) method.

The AHP is a MCDM approach that provides a sound mathematical basis for including both quantitative and qualitative attributes in terms of the numerical data and stakeholder judgments respectively. Further, AHP allows for the decomposition of a complicated problem using a hierarchy structure. AHP allows for the subjective evaluations that express the stakeholder's preferences for one decision parameter over another by pairwise comparisons using 1-9 ratio scale, known as the Saaty scale (Papalexandrou et al, 2008). This methodology allows for incorporation of uncertainty

which is inherent to the decision making process through the concept of a consistency ratio. The consistency ratio (CR) is taken as the ratio of the consistency of results being tested to the consistency of the same problem being evaluated with random numbers. If the CR is less than or equal to 0.1 then the pairwise comparisons and the priority weights thus obtained are sufficiently consistent and no further evaluation is needed. However if the CR is greater than 0.1, then the stakeholder preferences are not quantified sufficiently consistently and the preferences (expressed as pairwise comparisons) need to be re-evaluated (Alphonse, 1996). As a means of reconciling the multiple criteria capabilities of AHP, the methodology has further been augmented by incorporating fuzzy logic. Fuzzy logic is a form of multi-valued logic which allows for expression of the stakeholder's preferences in terms of linguistic variables such as GOOD and the inclusion of imprecise data (which characterize the quantitative data pertaining to biofuel production). The combination of AHP and fuzzy logic in the form of Extent Analysis based Fuzzy Analytical Hierarchy Process (AHP) has been used in this research (Chang, 1996 and Wang et al, 2008). This allow for the inclusion of qualitative judgments, preferences of the stakeholders and quantitative data within the decision making process.

1.5 Aims and Hypothesis

The aim of this research is to provide stakeholders with a decision support system to help determine the most sustainable biofuel materials (crops) and to pinpoint the policies which will lead to the production of these crops. Specific aims in this study include developing software functionalities which:

- Allow for the inclusion of both tangible and non-tangible factors including expert opinions, stakeholders' priorities and other non-quantifiable data.
- Enable systematic evaluation of the alternative options.
- Explore alternative options through the provision of sensitivity analysis to see the changes in the recommended option.
- Provide a foundation for developing a combination of new policies and techniques which balances the environmental impact of biofuel production with economic viability.

The research is based on the following hypotheses:

- MCDM can positively contribute to the realization of policy design for effective biofuel systems and assist policy makers in determining the future of biofuel policies through the incorporation of AHP and its proposed fuzzy extension.
- Fuzzy logic can directly impact the outcome of decision analysis, ensuring that the results of the software processing are specific, comprehensive, and include the relevant criteria.
- The software system will provide support for policy design for sustainable biofuel production and processing throughout a diverse range of geographic, economic, political, social, and technological scenarios.

As a practical means of achieving the aim of supporting stakeholder decision analysis, it has been decided to use the existing software Compendium (Compendium Institute,

2001) and extend it to allow for incorporation of stakeholder viewpoint and multi-criteria decision making in the context of long term stakes.

1.6. Organisation of Chapters

In order to detail the various components of this research, the Chapter outline is as follows:

Chapter 2: Literature Review: Demonstrates the imperative nature of biofuel integration into the global energy scheme. Also offers deeper empirical insight into the application of fuzzy set theory and role of MCDM (especially AHP) in sustainability related decision making.

Chapter 3: Methodology: Brief description of the concepts (AHP, fuzzy set theory) that have been used to develop software functionalities which have been incorporated in the base software Compendium as means of extending its scope.

Chapter 4: Software Descriptions: Describes the Compendium software: the design and working of the three functionalities (Options vs Fuzzy Criteria Matrix, AHP, Fuzzy AHP) that have been developed as the part of this research.

Chapter 5: Option vs Fuzzy Criteria Matrix: Demonstrates the working of the Option vs Fuzzy Criteria Matrix through case studies pertaining to the Philippines crop cycle and the land resource management which are directly associated with sustainable harvesting of these commodity crops.

Chapter 6: Evaluating Land for Crop Cultivation Using Fuzzy Logic: To demonstrate and implement the concept of approaching degree described using **fuzzy logic multifeature pattern recognition** tool. The strength of the approach tested herein lies in integrating fuzzy logic in an important decision making tool for identifying appropriate land for cultivation of crops.

Chapter 7: The AHP Case Study of Regions for Biofuel Crop Cultivation: Demonstrates the functionality of AHP implementation as a model of biofuel system design and crop optimization. Also highlights the mechanism for policy evaluation and cross-functional strategy design.

Chapter 8: Scenario Planning for Sustainability Policy through AHP: Describes how the AHP functionality has been used to identify optimal crops both under the current scenario and in context of the desired future scenario. Further the Chapter provides a framework for identifying optimal decision policies through a case study based model.

Chapter 9: Selecting Appropriate Biofuel Crop for Cultivation Using Fuzzy AHP: A case study model for land selection has been developed using the extent analysis based fuzzy AHP functionality. Apart from helping to identify the most robust option, this functionality also allows for the selection of optimal decision policies. Further, a framework has been provided to allow for scenario planning by enabling the testing of the possible impact of the selected decision policies on the future.

Chapter 10: Result Analysis, Discussion and Conclusions: This Chapter concludes by summing up the findings obtained from the various case study models that have been

developed using the different functionalities of Options vs Fuzzy Criteria Matrix, Analytical Hierarchy Process and Fuzzy Analytical Hierarchy Process designed as a part of this research. These findings are compared with inferences drawn from the existing literature as a means of testing the validity of results and the robustness of the software functionalities.

CHAPTER 2: LITERATURE REVIEW

The following sections present a comprehensive literature review which evaluates a broad range of theory and research regarding biofuels, fuzzy logic, and MCDM.

2.1. Biofuels Production Challenges

Different agricultural crops can be grown for the production of biofuels. Popular biofuel components as identified by Demirbas (2008) include rapeseed, soybean, palm and sunflower which are used to manufacture biodiesel, in addition to wheat, maize, sugar beet, and potatoes which are used for manufacturing bioethanol. These biofuels are increasingly being promoted as a viable substitute for conventional fossil fuels (Papalexandrou et al. 2008). The perceived benefits of biofuels (reduction of GHG emissions and energy security) are reflected in an ever increasing number of countries introducing or planning to introduce policies to increase their proportional share of biofuels in energy production (Mol, 2007). As of 2007, biofuel production was estimated at 35 billion litres, accounting only for a small part (2%) of the 1200 billion litres of annual gasoline consumption worldwide. But the contribution of biofuels to energy supply is expected to grow fast and this would entail an increased diversion of agricultural crops for the purposes of biofuel production (Fraiture et al. 2007).

Feedstocks used in current first-generation biofuel conversion technologies utilize conventional food and feed crops for producing biofuels. Depending on crop choice and management, agricultural intensification brought about by the increased biofuel demand can create significant environmental pressures on soil, water resources and biodiversity. The process of intensification, especially the use of agro-chemical inputs

(fertilizers, pesticides), may counteract the environmental sustainability goal of biofuel production (Fischer et al. 2009).

Koh and Ghazoul (2008) estimated that a substantial increase in cultivated area for all major biodiesel feedstocks, including soybean in the US (33.3–45.3 million ha), sunflower seed in Russia (25.7–28.1 million ha) and oil palm in Malaysia (0.1–1.8 million ha) will be needed to fulfil the increasing global demand for biofuels. Competition for scarce agricultural resources may increase prices of land, which may alter production costs and therefore affect the price of food and feed commodities (Fischer et al. 2009). This in turn could culminate in a possible increase in food prices. For 2.7 billion people who live on less than one dollar a day, the effects of rising food prices will be catastrophic (Cassman, 2007). This is because extremely poor people spend more than 50% of their income on food and even a marginal increase in food prices can put food out of their reach. In 2007 and 2008, price increases of staple foods reached alarming proportions which triggered concerns of a global food crisis. During this period, export prices of wheat increased by 130%, rice by 98%, and corn by 38% (Rahman et al. 2008). Even though the underlying causes of rising food prices are many and complex, it has been argued that out of all these causes, the diversion of crops and crop land for biofuel production remains an important factor (Koh and Ghazoul, 2008). The use of corn to produce bioethanol in the US has increased from 6% of total corn production to 23% over the last three years (Rahman et al. 2008), and this has undoubtedly contributed to tightening food supplies and rising food prices. Keleman and Rano (2008) have argued that increased

demand for corn based ethanol was an important factor in Mexico's 2007 "Tortilla Crisis"¹.

Besides food security, the increase in biofuel crops cultivation is also regarded as a potential cause of environmental pollution. In 2008, there was over 12.7 kg of nitrogen and an additional 31.29 kg of phosphorus added per acre of soil for this farming process. Of these additives, the IPCC suggested that nearly 20% is leached by runoff due to rainwater and irrigation (IPCC, 2006).

Despite its many advantages over petroleum-based fuels, biofuel production and use may result in significant negative consequences for biodiversity which may further contribute to environmental degradation (Groom et al, 2007). Razing of lush tropical rainforest which destroys an extremely rich and biodiverse ecosystem, as seen in the case of the South East Asian palm oil (Scharlemann, 2008) is an example of the negative impact of biofuel production on biodiversity. Current plans for biofuel infrastructure expansion and integration could reduce the Amazon forest cover from 5.4 million km² (2001, 87% of original area) to 3.2 million km² (53%) by 2050 (Malhi et al. 2008). However there are many different drivers to the deforestation of the Amazon (biofuel production being one of them) and the authors do not specify how much of this deforestation can be specifically be attributed to biofuel production.

There is no doubt that, destruction of the tropical rainforests for the purpose of biofuel cultivation in both South East Asia and the Amazon threatens the survival of many endemic species of flora and fauna (Koh and Ghazoul, 2008). However, Koh and

¹ Mid 2006 saw a spike in global petroleum prices. As a reaction to that, USA increased emphasis on corn based ethanol which in turn drove up the prices of maize significantly, the staple food crop of Mexico (Keleman and Rano, 2008).

Ghazoul have not provided substantial evidence to indicate how much of the destruction of the rainforests can be specifically attributed to biofuel demand and production.

Biofuels themselves are considered carbon neutral. Hill et al. (2006) reported that soybean biodiesel would produce nearly 41% less greenhouse gas (GHG) emissions than diesel fuel, while corn grain ethanol would produce 12% less GHG emissions than gasoline. However, the lifecycle process is not carbon neutral, and often can release more carbon in inefficient systems than fossil fuels would have produced (Doornbosch and Steenbilk, 2008). For instance, Fargione et al. (2008) suggested that the consequences of land clearing in order to meet the global demands for biofuels would cause a substantial increase in the overall GHG emissions due to soil disruption and foliage clearing between 17 and 420 times the potential reductions predicted from these fuel sources.

The world water system is already under heavy stress with agriculture taking a 70% share of world's total water resources. The cultivation of biofuel crops is further expected to add to pressure on water resources, depending on the type of crop and region (FAO, 2008). In terms of irrigation water, the share is slightly higher because of the relatively large share of irrigated sugarcane in the biofuel mix; sugarcane has irrigation requirements of 800 mm/Ha (FAO, 2008). As opposed to agricultural energy crops, *Jatropha* can grow on marginal land with limited water requirements.

If all national policies and plans for biofuels are successfully implemented, 180 km³ of additional irrigation water withdrawals will be needed. Globally around 7130 km³

of water is evapotranspired by crops per year, without accounting for biofuel crops (Molden et al. 2007a). Biofuel crops account for an additional 100 km³ (or around 1%). Total irrigation withdrawals amount to 2,630 km³ per year globally (Fraiture et al. 2007) of which 44 km³ (or 2%) is used for biofuel crops. Although globally this is less than a few percentage points of the total water use, the impact for certain countries including China and India could be highly significant, for water resources, and with feedback into global grain markets. It is unlikely that fast growing economies such as China and India will be able to meet future food, feed and biofuel demand without substantially aggravating already existing water scarcity problems (Fraiture et al. 2007).

This section has highlighted that much uncertainty and controversy surrounds biofuels as sustainable alternatives to fossil fuels and the current biofuel boom could quite rapidly be replaced by a bust. That is, the current biofuel production pathways could leave lasting negative consequences for the natural ecosystem but few lasting social benefits (Malhi et al. 2008). Hence, new strategies and policies must be implemented in order to meet global energy needs while reducing the overall impact of biofuels farming and production. In order to support the development of required policies and optimization methodologies, a decision support system is proposed that will make use of both MCDM (in the form of AHP) and fuzzy logic to investigate some of the aforementioned issues.

2.2. Multi Criteria Decision Making for Sustainability

Decision makers are increasingly seeking to design environmental and development policies that will support sustainable development (of biofuels). To support their

efforts, practical tools are needed to formulate sustainable development policies and clear methods to assess their acceptability and effectiveness (Abaza and Baranzini, 2002). One such tool is Multi Criteria Decision Making (MCDM). MCDM is aimed at supporting decision makers who are faced with making numerous and conflicting criteria. It aims at incorporating these criteria within the decision making process and deriving a way of reaching a compromise between them such that a suitable choice out of a number of options/alternatives may be selected. Further, MCDM is needed for decision-making for sustainability related policy design due to the complexity of issues and the inadequacies of conventional tools such as cost-benefit analysis (CBA), cost-effectiveness analysis (CEA) for capturing the full range of impacts of a policy or capital project (Browne et al. 2009).

MCDM can be regarded as an operational evaluation and decision support approach that is suitable for addressing complex problems featuring high uncertainty, conflicting objectives, imprecise data and information, multiple interests and perspectives, and the accounting for complex and evolving biophysical and socio-economic systems (Wang et al. 2009). However, MCDM does not facilitate the discovery of an ideal or optimum solution but allows for the creation and emergence of consensus around justified solutions or strategies. Furthermore, sustainability related policy formulation involves many value judgments regarding technical, socio-economic and environmental issues and, therefore, reaching clear and unambiguous solutions may be difficult (Cavallaro and Ciruolo, 2005).

The usefulness of MCDM to support decision making for questions concerning sustainable development, where conflicting objectives and multiple interest groups are

involved, has been increasingly acknowledged (Antunes and Oliveira 2004). Defining a sustainable development model for biofuel production requires reconciling of the objectives of economic prosperity, social issues and respect for the environment. Consideration of trade-offs between these conflicting parameters requires the prioritizing of various criteria and alternatives and the subsequent ranking of these alternatives as a first step towards establishing efficient policy strategies for biofuel sustainability (Tirado and Lopez, 2008).

MCDA methods differ in the way the idea of multiple criteria are executed.. In particular each method has its own way of assessing criteria, the application and computation of weights, the mathematical algorithm utilised, the model to describe the system of preferences of the individual facing decision-making, the level of uncertainty embedded in the data set and the ability for stakeholders to participate in the process (De Montis et al. 2000). Numerous MCDM methodologies are presented in the literature which can be used to aid the decision making process such as ELECTRE, PROMETHEE, TOPSIS, AHP and Goal Programming.

Goal Programming (GP) is less subjective than the other listed MCDM techniques, and it cannot handle qualitative data/elements (Ramanathan and Ganesh, 1995). This makes GP unsuitable as a standalone MCDM methodology for supporting sustainability related policy formulation as qualitative data and attributes are indispensable. Similarly, the Outranking Methods (comprising ELECTRE and PROMETHEE) represent preference information by the use of mathematical functions. This is rather complicated and difficult to explain to non specialists (Laukkanen et al. 2001). Therefore, outranking methods have been deemed to be less

suitable for use directly with stakeholders (Belton and Stewart, 2002). For all these reasons, Pohekar and Ramachandran (2004) have recommended AHP as a more robust MCDA technique for supporting sustainability related decision making.

2.3. Analytical Hierarchy Process

Various researchers over the past decades have integrated the AHP methodology into the analysis of diverse systems and as decision making tools, the aim being to ensure that the end decisions and objectives are relevant. This is because AHP can decompose a large system into a framework in which a diversity of inter-related factors such as social, economic and environmental, may be included. AHP helps to analyze the complex, mutual interactions, and impacts of the factors (Mei et al. 1989). AHP reflects the human way of thinking and hence provides a medium of communication between planners, decision makers, analysts, and researchers (Mei et al. 1989).

In the context of making decisions regarding energy and fuel provision, Dyer and Foreman (1992) state that AHP has an advantage because it can accommodate tangible and non-tangible criteria, and allows for individual and group factors to be considered. Ease of comprehension and interpretability of the results is the most important quality of a MCDM method in cases where the participation of the stakeholders is required (Kangas et al. 2001). This facility is adequately provided in AHP. Larson (2007) shows that the AHP methodology has a great deal of value when considering sustainability in engineering related applications. Poh and Ang (1999) demonstrated, in their study regarding energy options for Singapore that the ability of AHP to yield a hierarchy of results rather than one 'best fit' is vital because it allows

for the addition of complementary alternatives so it provides flexibility for future planning. The methodology has also been applied by the Victoria Department of Primary Industries for over a decade and has produced more than 50 commodity-based land suitability models which incorporated geographic criteria and participatory stakeholder inputs (Bishop et al. 2009).

Specifically in the case of evaluation of biofuel sustainability, Dinh et al. (2009) used the AHP system to identify the which biofuel option proves to be most favourable biofuel option when economic, technical and sustainability considerations are taken into account. It has been found that the use of AHP is extremely beneficial in accommodating the complex elements that contribute to sustainability. However, sustainability is an inherently complex concept whose scientific definition and measurement still lack wide acceptance. Fuzzy logic is well suited to handle such an uncertain and polymorphous concept (Phillis and Andriantiatsaholiniaina, 2001).

2.4. Fuzzy Logic

Many researchers have implemented fuzzy logic for various sustainability related decision making problems. Martinsen and Krey (2008) applied fuzzy optimization to energy systems modelling in Germany, to provide better representation of decision processes and find compromises between contradictory targets (such as economic viability, environmentally friendly and secure energy supply). Pramanik and Roy (2007) demonstrate the validity of such research measures, integrating fuzzy objectives as a tolerance boundary for multilevel policy design. This strategy relied upon the stakeholder value systems as input variables. Directly relevant to the biofuels analysis challenge, Kok (2009) integrated fuzzy modelling to determine the

valuation of Brazilian rainforests and their evolving deforestation patterns. Such conclusions offer policymakers a much more strategic opportunity for moderating wood harvesting and agricultural expansion based on diverse stakeholder value systems.

When multi-criteria evaluation systems are required, researchers turn to fuzzy logic as a way of evaluating both qualitative and quantitative variables. Many complicated scenarios with widespread national implications are evaluated using this formatting. For example, Hung et al. (2008) evaluated the potential for a fuzzy based MCDM evaluation system through which they were able to exploit vague system variables to mitigate uncertainty, and assist in decision-making.

The majority of sustainability related decision-making investigations involve contexts that are aggregate and variable; Gagliardi et al. (2007) suggested that fuzzy logic optimizes judgments based on various criteria defined within the scope of analysis. From a policy standpoint, such investigation is essential to define the project dynamics, environmental influence, and long-term impact based on specific ecological activity. Essentially, fuzzy logic and the prescription of fuzzy sets enable the definition of complex scenarios, which are too qualitative to be defined by mathematical analysis or a more classical quantitative methodology (Jiang et al. 2009). Strategically, fuzzy logic can be integrated into a wide range of processes and concepts. Sometimes fuzzy logic systems have been integrated into multi-criteria decision-making techniques as a means of incorporating qualitative judgements and imprecise data within the decision making process.

2.5. Fuzzy Multi Criteria Decision Making

MCDM is governed by the establishment of the ideal point or objective whereby creativity and invention can predict new methods of goal achievement in accordance with the ideology or prescribed rationale (Zeleny, 1982). As evidenced by Gomez Limon et al. (2003), MCDM investigation requires stakeholder opinions to optimize the variables and their rating scale on which the desired program is developed.

The use of combined fuzzy logic within the MCDM approach, (Fuzzy MCDM) enables direct translation of linguistic perspectives throughout the decision-making process. Chu and Lin (2009) established hierarchical applications for integrated fuzzy MCDM analysis models among varied subjective and objective criteria for decision making. Liang (1999) evaluated a combinative approach to fuzzy MCDM in which specific guidelines include the employment of linguistic terms. For the purposes of supporting sustainability related decision making, fuzzy MCDM was used for the development of conservation-tillage cropping systems for grain sorghum and wheat as a means of encouraging sustainable agriculture (Torbert et al. 2009). Liu (2007) made use of fuzzy MCDM, specifically fuzzy AHP for generating a new environmental sustainability framework which enabled evaluations of environmental sustainability in 146 countries to be calculated, ranked and clustered, and of obstacles to environmental sustainability identified. Although fuzzy set theory can be incorporated within any MCDM methodology, the research has focused on adapting fuzzy set theory within the framework of an Analytical Hierarchy Process (AHP) analysis.

2.6. Fuzzy AHP

Policy making for sustainability related issues constitutes a very special kind of decision-making. This kind of decision-making involves multiple stakeholders, each with their different set of priorities, judgments, expectations, numerous, possibly conflicting criteria and uncertain, imprecise data (Boulanger and Brechet, 2005). Sustainability related policy formulation involves socio-political, environmental, and economic value judgments of the various stakeholders involved in decision-making process (Chiou and Tzeng, 2002). To estimate precisely the sustainability of biofuels production is nearly impossible; to classify the stakeholders' assessments in terms of linguistic variables and degrees of acceptability of the criteria and options is more meaningful (Mendoza and Prabhu, 2003). Multiple criteria, economic, technical, and social need to be taken into consideration to achieve an optimal evaluation of various alternatives. In such a scenario, Fuzzy AHP has proved itself a flexible working tool that offers good communication between the variety of stakeholders, engineers, and decision makers (Anagnostopoulos et al. 2007).

Srdjevic and Medeiros (2008) concluded that traditional MCDM methods are not sufficiently robust when dealing with limited experimental data, human judgment, and the combination of quantitative measures and linguistic expressions. Fuzzy AHP, on the other hand, provides a conceptual basis for dealing with imprecise data and prioritizing the criteria on basis of stakeholder value judgments by extending the boundaries of traditional AHP by expressing preferences in terms of linguistic terms, which in turn are represented by triangular fuzzy numbers (Anagnostopoulos et al. 2007). Although fuzzy AHP is a more complex methodology for assessing composite properties than the traditional MCDM methodologies, the ability of fuzzy AHP to

deal with uncertainty and qualitative and quantitative elements makes it suitable for providing decision support for multi disciplinary problems (Percin, 2008). Entani and Tanaka (2005) identify that one of the problems, with regard to AHP, is that a pair-wise comparison matrix is based solely upon the decision-maker's perception of relative importance and leads to a linear order of alternatives. The problem that arises from these elements is that it adds ambiguity to the calculation that may distort results. However, if fuzzy logic is introduced into the pair-wise comparison element of the analysis this ambiguity can largely be eliminated. For this reason, Fuzzy AHP in the recent past has been used to provide decision support for many sustainability related issues.

Fuzzy AHP has been utilized to analyze various policy strategies for public participation in formulation of transport policies (Arsalan, 2009), land selection for cultivation of agricultural crops (Prakash, 2003) and sustainable tourism development (Tsuar and Wang, 2007). Fuzzy AHP has been applied to the ranking of several long-term policy scenarios for water management in Brazil (Srdjevic and Medeiros, 2008). Hence, besides allowing selection of suitable options, this methodology can also serve as a building block for supporting the formulation and evaluation of sustainability policies (Tran et al. 2002).

Fuzzy AHP (and AHP) further have a provision for supporting scenario planning, a method to allow for strategic long term flexible planning.

2.7. Scenario Planning

The central idea of scenario planning is to consider a variety of possible futures that includes many of the important uncertainties in the system rather than to focus on the accurate prediction of a single outcome (Peterson et al. 2003).

Scenarios provide a mechanism for improving the understanding and management of ecological and social processes by scientists and decision makers with greater flexibility than conventional techniques could afford. Scenarios and scenario analysis have become popular approaches in organizational planning and participatory exercises in pursuit of sustainable development (Duinker and Greig, 2006).

Scenario planning has been defined as “a process of positing several informed, plausible and imagined alternative future environments in which decisions about the future may be played out, for the purpose of changing current thinking, improving decision making, enhancing human and organization learning and improving performance” (Chermack, 2004). In this context, scenario planning and MCDM share many commonalities, suggesting a potential for substantial synergies in seeking to use the scenario planning approach as a means of fostering a deeper understanding of external uncertainties in MCDM (Figueira et al. 2005). MCDM has been used as a means of allowing developing scenarios for sustainable forest planning which involved taking inputs from stakeholder groups while designing the relevant policies (Sheppard and Meitner, 2005).

Scenario planning involves combining factual data and expert evidence to create reasonable and credible scenarios envisioning possible future outcomes (Sorensen et

al. 2005). Scenarios may also provide a venue for testing new decision policies by manipulating forces and potential responses to them in an experimental environment. Decision-makers can play out the possibilities of given decision policies and examine their long-term effects (Chermack, 2004).

AHP has been used for the development of socio-economic scenarios which were then used to analyse the medium and long-term (2020, 2050, and 2080) climate impact on agricultural land use in Europe by linking agricultural land use with environmental and socio-economic variables (Abildtrup et al. 2006). In the case of biofuels, a scenario planning approach has been used for the modelling of (four) prospective scenarios in order to pinpoint options and actions which may promote sustainability and efficiency within the biodiesel supply chain (Vaccaro et al. 2009).

In the context of the present research, scenario planning has been explored as means of providing a framework for testing the plausible long-term impact of decision policies and as means of assigning values to the pairwise comparisons (Meade and Sarkis, 1998). The forward-backward mechanism has been used which allows for a detailed evaluation of the case study based models. According to Foreman and Gass (1998), by use of such methods, it is possible to identify novel outcomes that may help in achieving the desired results, and to investigate how these may change due to policy interventions.

To conclude the Chapter, it should be noted that the promotion of biofuels requires a robust national/regional planning response involving all stakeholders and consultation with national and international sources of scientific validation (ADB, 2007).

CHAPTER 3: METHODOLOGY

Sustainability-related decision making is a complex process. Decisions have to be made in the face of missing information and uncertainty over the confidence that can be placed on the available information (for instance biofuel sustainability-related decision making is fraught with imprecise data, i.e. data which are better described within a range of values rather than one single number). Decisions affect, and therefore need to involve, a broad range of stakeholders who may have different views/preferences on what attributes distinguish better from less desirable options. Furthermore, when sustainability is concerned, the decision stakes are high (Mitchell et al. 2004).

This research aims to provide a decision support system for the formulation of policies to enable the sustainable production of biofuels. Sustainability related issues pertaining to biofuel production need to allow for the incorporation of imprecise data (in a flexible way, keeping in mind that data can change over time), range of viewpoints/preferences and allowing for investigation of the sensitivity of the model. For the purposes of developing the decision support system, an open source Java based software; Compendium (Compendium Institute, 2001) has been used as the base software². Compendium allows the decision problems to be structured on a visual interface. This research has extended the scope of Compendium by adding software functionalities that now allow it to be used as quantitative decision support tool.

² Compendium software has been described in a greater detail in Chapter 4.

This Chapter describes the concepts and methodologies that have been used to design the software functionalities. These are: Fuzzy logic, the Analytical Hierarchy Process and a combination of the two, Fuzzy AHP. Chapter 4 will outline the design of the new software functionalities that have been developed using these concepts: (1) Options vs Fuzzy Criteria, (2) Analytical Hierarchy Process, and (3) Fuzzy Analytical Hierarchy Process.

3.1. Theory of Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process comprises the objective GOAL at the first level followed by the relevant CRITERIA³ at the second level. These criteria in turn may be divided into a number of SUB-CRITERIA which are present at the third level. For instance, the broad criteria of agricultural performance may have a number of associated sub-criteria, such as yield/hectare, fertilizer requirements and irrigation needs. The fourth level of the hierarchy comprises OPTIONS which may be associated with each of the sub-criteria (and the parent criteria). This four level hierarchy is shown in Figure 3.1.

³ In this case criteria means the standard measurement that can be used as the basis to judge something; in this case sustainability of a given biofuel production system. Sustainability criteria include GHG Savings, no raw material from undisturbed rainforests, no conversion of wetlands among others (European Commission, 2008).

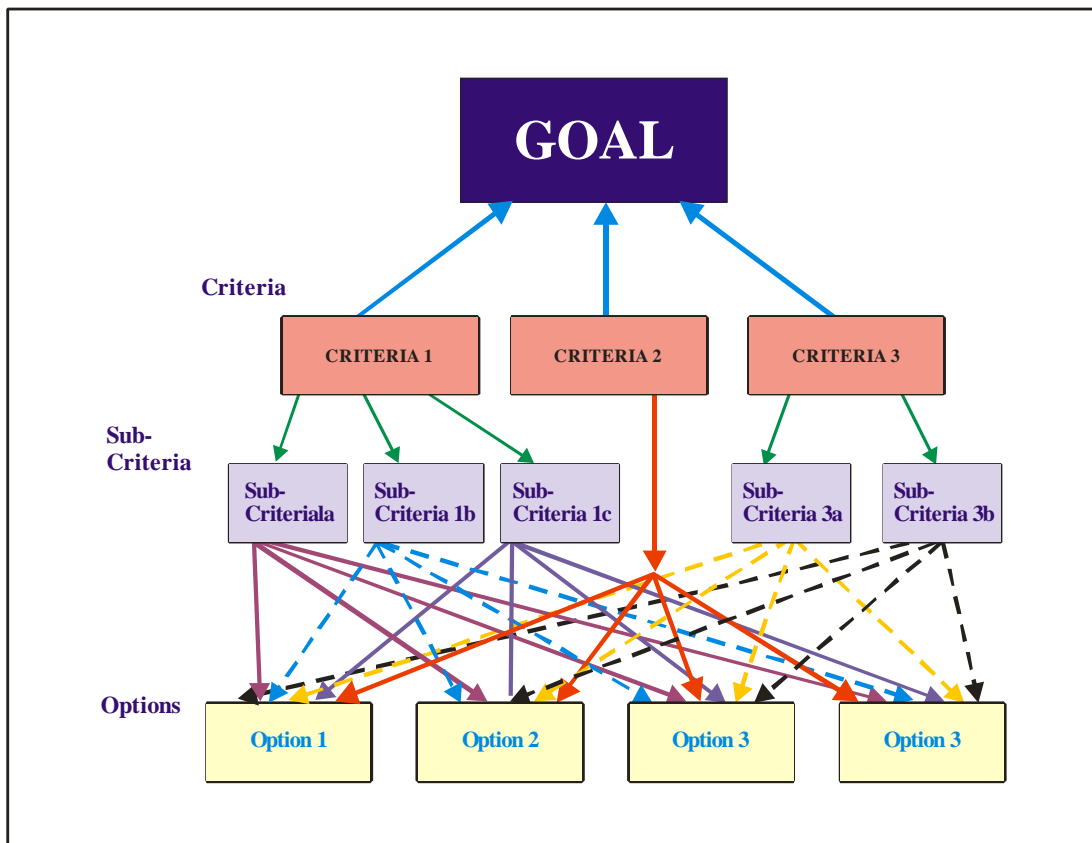


Figure 3.1: Four Level AHP Structure

The AHP methodology revolves around three steps: (a) identify goal, (b) identify criteria and sub-criteria affecting a decision, and (c) identify alternatives/options from which we need to choose the optimal. Pair-wise comparison is used to identify the relative weighting of criteria, that is, examining two criteria and addressing whether one is considered more important than the other. This level of importance can be recorded on a nine-point scale (Saaty, 1980) in order to generate the priority weighting between criteria. This is done through expert opinion or through comparison of empirical data. The 1-9 point scale studied by Saaty and Vargas (2001) is widely accepted in AHP community and it is described as follows:

| Intensity of Importance | Definition | Explanation |
|--------------------------------|-----------------------------|--|
| 1 | Equal Importance | Two activities contribute equally to the objective |
| 2 | Weak Importance | Experience and judgment slightly favour one attribute over the other |
| 3 | Moderate importance | Experience and judgment moderately favour one attribute over the other |
| 4 | Moderate plus | Intermediate value between moderate and strong |
| 5 | Strong importance | Experience and judgment strongly favour one attribute over the other |
| 6 | Strong plus | Intermediate value between strong and very strong |
| 7 | Very Strong or Demonstrated | An attribute is favoured very strongly over the other |
| 8 | Very Very Strong | An attribute is vitally more important than the other |
| 9 | Extreme Importance | The attribute has the highest possible affirmation over the other. |

Table 3.1: The Fundamental Scale of Importance (Saaty and Vargas, 2001)

A pairwise comparison matrix can be created which depicts the stakeholder preference of one criterion over another using the aforementioned scale. The diagonal

elements of the comparison matrix are taken as unity and the rest of the elements are chosen by the reciprocal force, that is,

$$a_{ij} = \frac{1}{a_{ji}}, \quad \forall (i, j). \quad (\text{Saaty, 1980}) \quad (3.1)$$

This matrix \mathbf{A} is then used to determine the local priority weights of the criteria as an eigenvector corresponding to the maximum eigenvalue of this pairwise reciprocal comparison matrix, that is,

$$\mathbf{A} \cdot \mathbf{x} = \lambda_{max} \mathbf{x} \quad (3.2)$$

In this equation, λ_{max} is the largest eigenvalue of matrix \mathbf{A} and \mathbf{x} is the corresponding non zero Eigenvector (Saaty, 1980). The normalized eigenvector \mathbf{x} gives the value of the priority vector \mathbf{w} . For an $n \times n$ square matrix, the priority vector is denoted by

$$\mathbf{w} = (w_1, w_2, \dots, w_n)^T, \quad (3.3)$$

where T is the transpose of a vector. The consistency of the matrix \mathbf{A} is checked by calculating its consistency index (CI), expressed as

$$CI = \frac{\lambda_{max} - n}{n - 1}, \quad (\text{Saaty and Vargas, 2001}) \quad (3.4)$$

where n refers to the total number of compared criteria. When $CI = 0$, the comparisons are perfectly consistent but when it is not so then the decision maker can determine the level of inconsistency by comparing the CI with the Random Index (RI) from the **Eigenvalue method** (Saaty, 1980).

| | | | | | | | | | |
|------------|---|---|------|------|------|------|------|------|------|
| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| R I | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

Table 3.2: Random Consistency Index (RI) (Saaty and Vargas, 2001)

The consistency ratio $CR=CI/RI \leq 0.1$ is taken to be an acceptable level of inconsistency for a pairwise comparison matrix (Teknomo, 2008). In this case, the assignment of relative values is consistent and the priority vector obtained can be accepted as the priority weights of the criteria and sub-criteria. The normalized priority weights of various criteria, sub-criteria and options are then used to compute the absolute weight (W^a). If $CR > 0.1$, it is necessary to re-evaluate the assigned importance and restart the calculation.

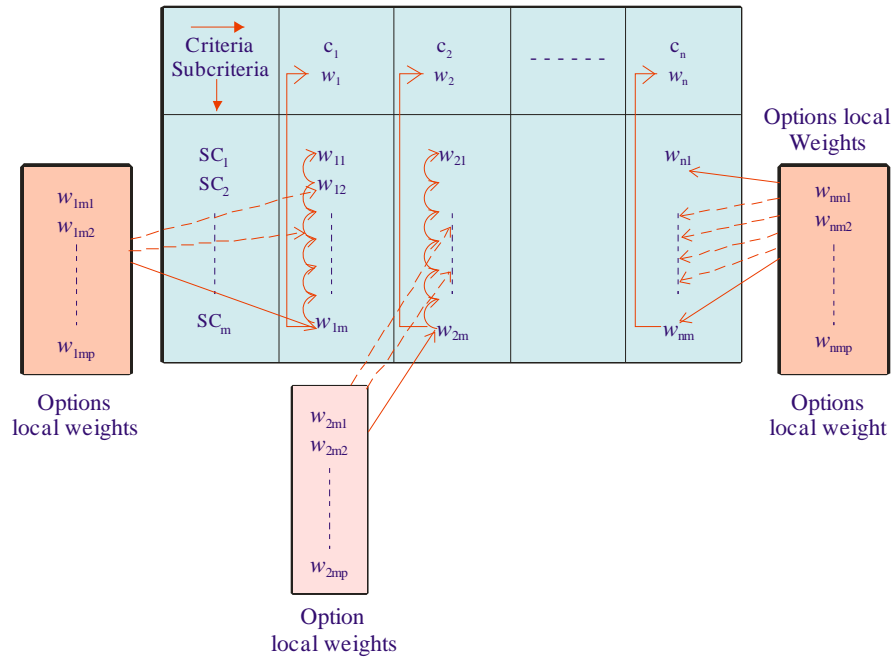
The absolute weight of a given criterion is calculated by multiplying the priority weights of the criterion with its associated sub-criteria priority weight. The value thus obtained is multiplied with the priority weights of all the associated options within the hierarchy structure tree. Let there be n criteria with local weights w_1, \dots, w_n ; each criterion has further m sub-criteria with local weights $w_{i1}, \dots, w_{im}, i=1,2,\dots,n$. If O_k is the k^{th} option with local weights w_{kij} with respect to sub-criteria j of the criteria i , then absolute weight of O_k is computed by

$$W^a = \sum_{i=1}^n w_i \sum_{j=1}^m w_{ij} w_{kij}, \quad k = 1,2,\dots,p \quad (3.5)$$

where p is the total number of options.

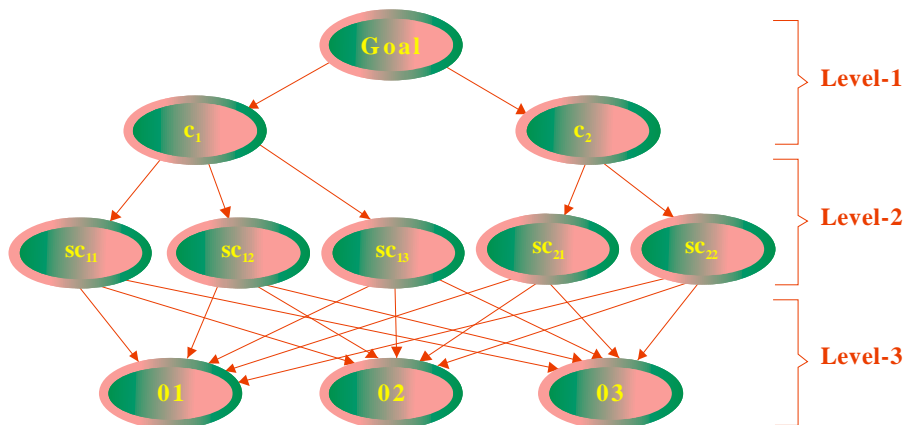
In a three level hierarchy, let there be n – criteria C_1, C_2, C_n at level 2, each having m sub-criteria $SC_1, SC_2 \dots, SC_m$ at level 3, while level 4 has p -options O_1, O_2, \dots, O_p to rank.

Although the number of sub-criteria associated with each criterion may be different, for convenience in representation, they are all set equal to m . The three - dimensional local weights matrix can be visualized as follows, in Figure 3.2 :



**Figure 3.2: Aggregation of Priority Weights for 4 Level AHP Structure
Three dimensional local weights matrix**

Figure 3.3 provides a diagrammatic illustration to explain the calculations of aggregate weights of the various options.



**Figure 3.3: Simple Illustration of Aggregation of Priority Weights
Two dimensional local weights matrix**

Suppose we have two criteria C_1 & C_2 where C_1 further has three sub-criteria SC_{11} , SC_{12} , SC_{13} , while C_2 has two sub-criteria SC_{21} , SC_{22} , at next level 2. Let there be three options $O1$, $O2$, $O3$ to rank at the last level 3. We compute the local weight of each node in the above hierarchical tree by finding out the priority vector (or the normalized Eigen vector) of the corresponding AHP matrix at that level. Let w_i ($i = 1, 2$) denote the local weight of C_i ($i = 1, 2$); w_{ij} ($i = 1, 2$) ($j = 1, 2, 3$) denote the local weight of sub-criteria SC_{ij} ; and w_{kij} ($k = 1, 2, 3$) ($i = 1, 2$) ($j = 1, 2, 3$) criteria C_i and sub-criteria SC_{ij} .

The aggregate absolute weight of option OK is given by

$$W_k = \sum_{j=1}^2 w_i \sum_{j=1}^3 w_{ijk} w_{ij}, \quad k = 1, 2, 3. \quad (3.6)$$

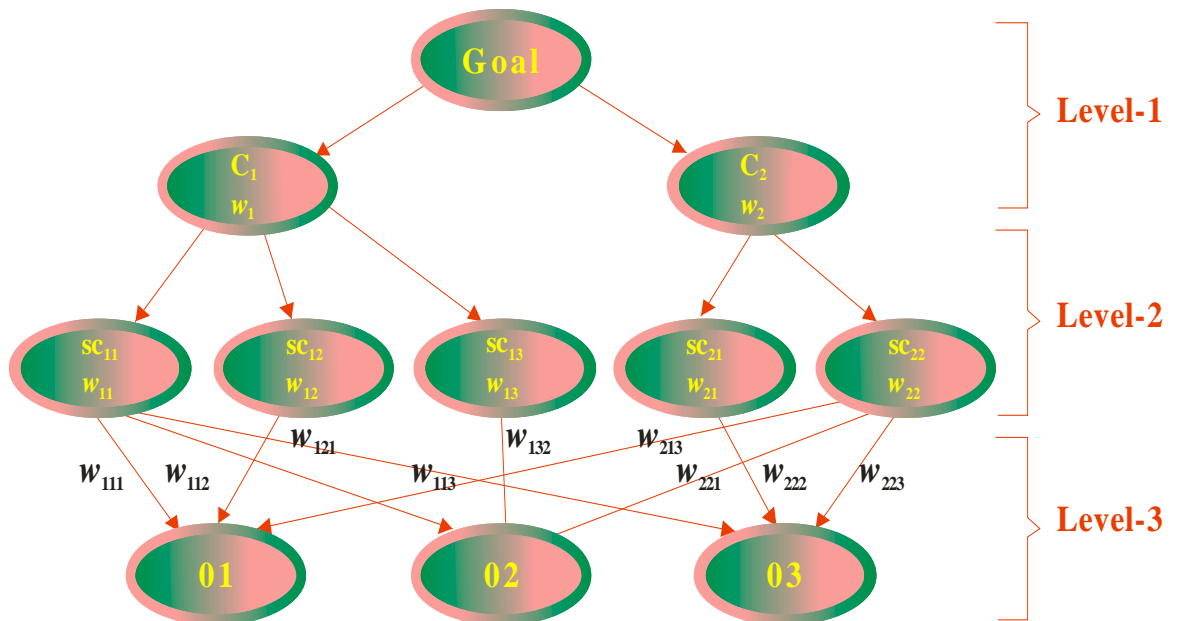


Figure 3.4: Simple Illustration of Aggregation of Priority Weights With local weights of the options Two dimensional local weights matrix

Some of the local weights of the options O1, O2 ,O3 are shown in Figure 3.4. Each option node is connected to each sub-criteria node and the edge connecting them has weight w_{ijk} .

In general, using the above notations then for the i^{th} criteria ($i = 1, 2, \dots, n$) with local weight w_i , having $i(m)$ sub-criteria with local weights w_{ij} , $j = 1, 2, \dots, i(m)$, the absolute weight of the k^{th} option relative to criteria c_i is given by

$$W_k = \sum_{i=1}^n w_i \sum_{j=1}^{i(m)} w_{ijk} w_{ij}, w = 1, 2, \dots, p \quad (3.7)$$

Where p is the total number of options to be ranked and w_{ijk} is the local weight of the k^{th} option relative to sub-criteria j of the criteria i .

After calculating the absolute weights associated with a given criterion, we multiply it with the corresponding data values.

However, the data collected for the purpose of selecting an optimum option from a number of available alternatives may be of different units and orders of magnitude. Hence, there is a need to condition the data into similar units by the use of data conditioning techniques like normalizing or indexing. For the purpose of this research, indexing of data has been carried out as it allows the criterion-related data to be expressed in the form of a dimensionless ratio. This is achieved by dividing the numerical data by a single performance value with the same units. For the purpose of indexing the actual data, the element in the first cell of each row is regarded as the base and the rest of the elements in that row are divided by the selected performance value to generate the ratio scales (Chee Tahir, 2006).

An optional provision for grading of indexed data is provided which allows the user to scale and order the indexed quantitative data so it falls within the range of a specifically chosen scale. The quantitative data may be graded using a linear interpolation equation (Chee Tahir, 2006):

$$S = \frac{P_{data} - P_{low}}{P_{high} - P_{low}} * 100, \quad (3.8)$$

where P_{data} is the numerical data of the given criterion and P_{high} and P_{low} are the limiting values corresponding to respectively the best and the worst case for the given criterion. These values are taken from the national or industry-related data for the given criterion.

The graded data and the absolute weights (W^a) are subsequently used to derive the final ranking of the p options by using the expression:

$$Total\ Marks_{ok} = \sum_{j=1}^m S_{kj} * W^a_{kj}, \quad k = 1, \dots, p. \quad (3.9)$$

Here, $Total\ Marks_{ok}$ denotes the total marks obtained by k -th option. The options are then ranked in descending order of their total marks.

Further, there is a scope for performing a sensitivity analysis within the methodology.

Sensitivity analysis is used to determine how “sensitive” a model is to changes in the value of the parameters of the model and to changes in the structure of the model (Bereierova and Choudhari, 2001). It does so by studying how variation in the output of the mathematical model can be attributed to different sources of variation in the input of the model. Problems met in sustainability-related and decision support

systems may entail the use of mathematical models, which generally do not embody a straightforward relationship between input factors (what goes into the model) and output. Such an appreciation, i.e. the understanding of how the model behaves in response to changes in its inputs, is of fundamental importance to ensure a correct use of the models.

For the purpose of this research, sensitivity analysis serves the purpose of supporting decision making or development of recommendations for decision-makers and enhancing the communication between the model and the users. The impact of the stakeholders' preferences is represented by variation in the priority weight of criteria. By performing a sensitivity analysis, the user can see how the change in preference for a given criterion changes the recommendation produced by the model. Sensitivity analysis can be performed by changing the priority weight of a criterion j and observing the resulting changes to the ranking of an otherwise recommended option (Chee Tahir, 2006).

$$W_{c_{new[j]}} = W_{c[j]} * (1 + p) \quad (3.10)$$

Here $W_{c(j)}$ is the priority weight of the criterion j on which the sensitivity analysis has been performed and p is the value by which the priority weight of the criterion is varied. The $W_{c_{new(j)}}$ is the new priority weight of the criterion thus obtained. Given that the sum of the priority weights of the criteria must be 1, the weight of remaining relative criteria c, i has to be changed accordingly.

$$W_{c[i]} = W_{c[i]} - \left(p * \frac{G}{1 - G} * W_{c[i]} \right) \quad \text{where } I \neq j \quad (3.11)$$

Here, $W_{c(i)}$ is the priority weight of the remaining criteria and $G = W_{c(j)}$.

The new recommendations produced by the system can allow the users to decide which alternative would be more feasible under a given of input conditions.

The present work extends the model of Saaty by incorporating the fuzzy set theory to enhance the capabilities of the model. The basic principle of this extension has been outlined in section 3.2 and 3.3

3.2. Fuzzy Set Theory

Fuzzy logic is a form of multi-valued logic derived from fuzzy set theory to deal with reasoning that is approximate rather than precise. In fuzzy logic, the degree of truth of a statement ranges between 0 and 1, and unlike classic logic, is not constrained to the two truth values {true, false}. It can handle the concept of partial truth-values between “completely true” and “completely false”. In conventional logic the degree to which individual element is a member or not a member of a given set is expressed in terms of membership functions where the membership function can only take a value of either 0 or 1. On the other hand, the idea behind fuzzy logic is to describe the vagueness of the entities in the real world where the notion of belonging to a set is a matter of degree (Malczewski, 1999); that is, transition between membership and non-membership functions is gradual rather than abrupt. Mathematically, A is a fuzzy subset of X , that is $A \subset X$, and a membership function $\mu_A(x)$ defines a membership in the set A . The membership $\mu_A(x)$ assigns to each x a value in $[0, 1]$, indicating the degree of membership of x in A . Membership functions, are therefore functions that map x from X into the interval $[0, 1]$ (Cornelissen et al. 2001).

Membership functions are at the core and define the degree to which a given criterion contributes to issue at hand (e.g. suitability of a given geographical zone for the cultivation of a given crop). The triangular membership function (TFN) is used in this study for computational simplicity, and moreover the assessment results we obtained later from our model agree with the widely observed patterns. A triangular fuzzy membership function is described using three control points [a, b, c] which govern the shape of the membership functions

$$\begin{aligned} \mu_A(x) &= \frac{x-a}{b-a} && \text{if } a \leq x \leq b \\ &= \frac{c-x}{c-b} && \text{if } b \leq x \leq c \\ &= 0 && \text{otherwise} \end{aligned} \quad (3.12)$$

The first control point, a, indicates the location where the membership function starts to linearly increase above zero until the maximum of 1 is reached at the second control point b. Thereafter, the membership function starts to linearly decrease below 1 until minimum zero is reached at the control point c.

Linguistic variables such as LOW, MEDIUM, HIGH, etc. can be described by appropriate membership functions. Fuzzy logic allows inclusion of perception-based information within the decision matrix, thereby taking into account both value judgments and objective facts and data (Zadeh, 2000). It provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy or missing input information because, unlike an engineering system, the majority of the criteria being dealt with as a part of the present research cannot be described using an explicit numerical values. Given that a number of criteria encountered in this research are qualitative in nature and hence can be described using linguistic variables such as

LOW and HIGH (which in turn can be described between lower and upper numerical bounds), the concepts of linguistic variables, fuzzy numbers and defuzzification have been used in the following steps:

- a) Initialization: This step is essentially concerned with the preparation of the decision-making process. Several issues are incorporated in this step, which include, defining the decision issue at hand and selecting the requisite options and criteria. The dialogue mapping facility of the base software Compendium is greatly beneficial for this stage.
- b) Identification of Linguistic Data: The criteria associated with the decision making process are identified and their values and/or importance in turn are expressed in terms of linguistic variables such as LOW, MEDIUM, etc. The values of these linguistic variables in turn are expressed between ranges of values.

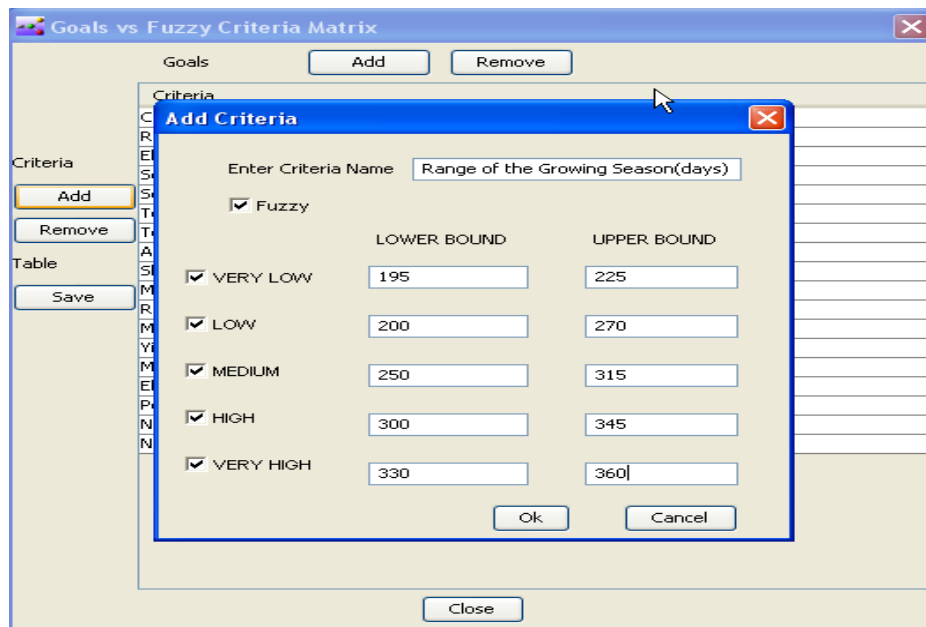


Figure 3.5: Bounds of fuzzy linguistic expressions

The GUI in Figure 3.5 shows that, the user can specify a given criterion (in this case, the range of growing season) as fuzzy and select the linguistic variables associated

with the fuzzy criterion. The upper and lower bounds of the linguistic variables are user-specified.

- c) Fuzzification of Input Data: This allows the boundaries of the linguistic variables describing the fuzzy criterion to overlap. This is a distinct advantage of fuzzy numbers that it provides the conceptual basis for dealing with uncertainty arising out of imprecise boundaries between various different categories (McBratney and Odeh, 1997). In Figure 3.6, membership functions of three linguistic variables, MEDIUM, HIGH and VERY HIGH are created to describe rainfall (in mm). Medium rainfall can be described between the lower and upper bounds of 250mm to 620mm. Similarly High and Very High rainfall are respectively fixed between the lower and upper bounds of 450mm-1300mm and 1100mm-1500mm. The values of the membership functions may or may not overlap (in this case, they do).

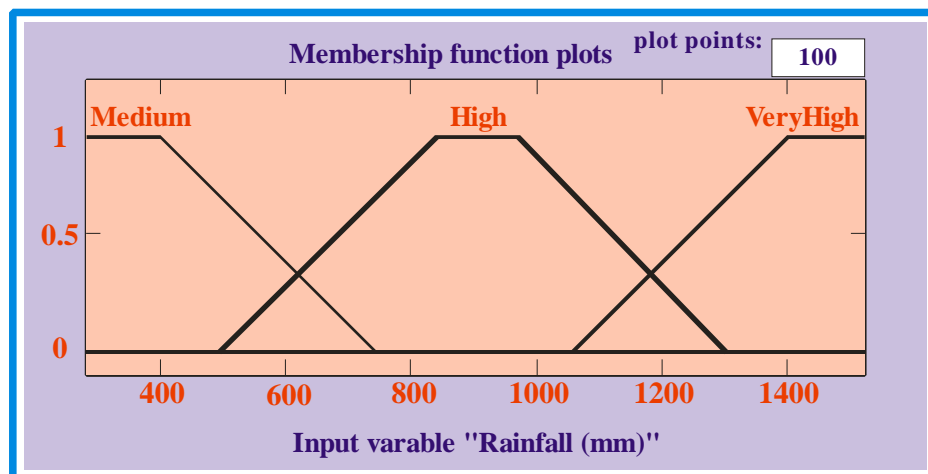


Figure 3.6: Trapezoidal Membership Functions to describe Rainfall (mm)

- d) Defuzzification: After generating the membership functions on the basis of lower and upper bounds provided by the users, the next step is to carry out a defuzzification process which yields the final numerical value. Out of a number of

methods available for defuzzification, the Centre of Gravity method (COG) also known as the centroid method is one of the most frequently applied methods (Nasibov and Mert, 2007) and is selected in our study. The centre of gravity of a triangular membership is analytically obtained by calculating the x-coordinate of the centroid, C_x :

$$C_x = \frac{\int \mu_2(x) x dx}{\int \mu_2(x) dx} \quad (3.13)$$

A similar approach for defuzzification of trapezoidal membership function has been used by Nasibov and Mert (2007).

The aforementioned concepts have been used to design the software functionality of **Options vs Fuzzy Criteria Matrix**. This allows the conceptual expectations of the stakeholders, namely policymakers and farmers, to be introduced into the decision-making process as inputs using linguistic variables. This ability of the functionality in turn allows interpretation and quantification of vague descriptive language supplied by stakeholders and subject experts.

A particular application of the fuzzy set theory, namely “*multifeature pattern recognition*” (Ross, 2005), is also implemented herein. The following text briefly explains the working and the theory behind the method.

For the purpose of applying the given methodology, the “approaching degree” concept is used to compare the new data pattern (in this case C) with some of the known data patterns (in this case P). Suppose the new data sample (that of the crops) is characterized by m features as a collection of non interactive fuzzy sets

$$C = [C_1, C_2, \dots, C_m], \quad (3.14)$$

where each C_i is a fuzzy set described by a TFN. In other words we denote by a fuzzy set C as the vector comprising of m components where each component C_i is a fuzzy set characterizing the i^{th} attribute, described by the linguistic variable, for the data. So, it is given that the new data set is characterized by m features, and each of the known patterns, say P_i , too is described by m features

$$P_i = [P_{i1}, P_{i2}, \dots, P_{im}]. \quad (3.15)$$

If some of the criteria are more important than the others, we can introduce the normalized weighting factors w_j with the j -th criterion such that

$$\sum_{j=1}^m w_j = 1. \quad (3.16)$$

However, for the purpose of the present research, the importance of all the criteria is assumed to be equal and hence all are assigned the weight $1/j$. The approaching degree of pattern C with patterns P_i is described by

$$(C, P_i) = \sum_{j=1}^m w_j (C, P_{ij}), \quad (3.17)$$

where each operation in the preceding expression is determined using the method of approaching degree described as follows. Here Equation 3.18 is the formula for calculating the Approaching Degree (AD).

$$(C, P_z) = \frac{1}{2} [(C \bullet P_z) + (C \oplus P_z)], \quad (3.18)$$

and
$$C \bullet P_z = \bigvee_{i=1}^n (c_i \wedge p_{zi}), \quad (3.19)$$

$$C \oplus P_z = \bigwedge_{i=1}^n (c_i \wedge p_{zi}). \quad (3.20)$$

The maximum approaching degree indicating the closeness of sample pattern C to the known patterns P_i is defined by

$$(C, P_i) = \max_{1 \leq i \leq c} \{(C, P_i)\}. \quad (3.21)$$

It may be noted that when the collection of fuzzy sets $C = [C_1, C_2, \dots, C_m]$ reduces to a collection of crisp singletons, that is, $C = [c_1, c_2, \dots, c_m]$, then the approaching degree is given by

$$\mu_{P_i}(C) = \sum_{j=1}^m w_j \mu_{P_{ij}}(C_j). \quad (3.22)$$

As before the maximum matching degree of singleton $\{c\}$ closest to pattern P_i is defined by

$$\mu_p(c) = \max_{1 \leq i \leq k} \{(\mu_{P_i}(c))\} \quad (3.23)$$

The index r which yields the maximum value for the approaching degree in the above expression is the most suitable class, among all alternative classes, for the new pattern C .

In Chapter 6, **Multifeature Pattern Recognition** is used to select a suitable zone for the cultivation of a given crop in Philippines, where the classes P are represented by various geographical regions of the Philippines and the crop under consideration is represented by C . Fuzzy set theory has been used both independently and within the scope of Analytical Hierarchy Process to enhance the capabilities of the decision support system.

3.3. Fuzzy Analytical Hierarchy Process

Even though the purpose of AHP is to capture expert knowledge, the conventional AHP falls short in situations where uncertainty is present (Kharman et al, 2004). The vagueness and uncertainty of the data used renders the pairwise comparison of the classical AHP insufficient when it comes to expressing the relative importance of one criterion over another. The earliest work on fuzzy AHP was done in 1983 in which vanLaarhoven and Pedrycz used fuzzy AHP for selecting the best option out of a number of available alternatives. Buckley, in 1985, extended Saaty's AHP methodology to deal with imprecision and subjectiveness of the pairwise comparison. Mahmoodzadeh et al, (2007) see Fuzzy AHP as an "extension of AHP to efficiently handle the fuzziness of the data involved in the decision-making." In other words, the fuzzy AHP acts as means of allowing vague data to fit into the hierarchy, enabling the subtleties in the analysis to be captured that would otherwise be lost. However, in order to capture such subtleties and uncertainties, a fuzzy pairwise comparison scale is required (Kwong and Bai, 2002). Using the concepts of the fuzzy set theory and the hierarchical structure analysis, Gumus (2009) designed a scale, analogous to the Saaty's 1-9 point scale, describing the linguistic terms and their corresponding triangular fuzzy numbers; this scale is described below in Table 3.3.

| LINGUISTIC TERMS | TRIANGULAR FUZZY NUMBERS |
|------------------|--------------------------|
| Equal | (1,1,1) |
| Weak Advantage | (1,2,3) |
| Not Bad | (2,3,4) |
| Preferable | (3,4,5) |
| Good | (4,5,6) |
| Fairly Good | (5,6,7) |
| Very Good | (6,7,8) |
| Absolute | (7,8,9) |
| Perfect | (8,9,10) |

Table 3.3: Fuzzy Comparison Measures

The incorporation of the fuzzy approach by means of fuzzy comparison scale, used to generate fuzzy pairwise comparison matrices, makes use of the triangular fuzzy numbers to represent uncertainty and vagueness (Liang and Wang, 1994).

The Fuzzy AHP essentially does two things:

- First, it allows for the incorporation of stakeholder preferences using linguistic variables
- Second, fuzzy data⁴ can be included for the purpose of evaluation.

A number of methods have been developed to handle fuzzy comparison matrices. The extension of research that is being pursued is to adapt the *extent analysis approach of fuzzy AHP* proposed by Chang (1996) in order to develop the software functionality for it. Fuzzy extent analysis is used to solve the fuzzy reciprocal matrix for determining the importance of criteria and alternative performance (Deng, 1999). This

⁴ Refers to the data that lies between a range of values rather than being defined by a single value.

method obtains crisp priority weights from a triangular fuzzy comparison matrix in four steps using the fuzzy arithmetic rules. The brief outline of the four steps involved are as follows: (i) sum up each row of the fuzzy comparison matrix, (ii) normalize the row sums, (iii) compute the degree of possibility of the i-th criteria over all other criteria by prescribed mathematical rules (Chang, 1996), (iv) finally compute the priority weights using the possibility degrees. The detailed procedure can be found in (Chang, 1996). Wang et al. (2008) suggested some modifications in the previous version of fuzzy extent analysis, to remove inconsistencies.

Example:

An application of the extent analysis fuzzy AHP methodology is described in this section based on the problem of identifying the most appropriate land for biofuel crop cultivation in the Philippines. The data are not crisp but lie between certain ranges for each of the criteria pertaining to the land type as shown in Table 3.4.

| Type of PEZ (Pedo Ecological Zone) | Elevation | Slope | Average Temperature |
|---|-------------------|-----------------|----------------------------|
| Warm Lowlands | Low (0-100 m) | Very low (0-8%) | Very High (25°C-42.2°C) |
| Warm-cool uplands | Medium (100-500m) | Medium (0-18%) | High (22.5° C - 25°C) |
| Warm-cool hilly lands | Medium (100-500m) | Medium (0-18%) | High (22.5° C - 25°C) |
| Cool highlands | High (>500 m) | Steep (33-100%) | Low (17°C- 20 °C) |

Table 3.4: Data Ranges (FAO, 2001)

In the fuzzy extent analysis, an experts' uncertain judgement can be represented by triangular fuzzy numbers (TFNs) (Vahidnia et al. 2009). Hence, the data in Table 3.4 is firstly converted into the TFNs, for instance, 0-100 is taken as (0, 50,100), 25-42.2 is taken as (25, 33.6, 42.2). The middle value is the midpoint of the lower and upper bounds (Klir and Ayyub, 2006). These TFNs, shown in Table 4.5, are used for pairwise comparison scale of the fuzzy extent analysis. The general form of a 3x3 fuzzy criteria matrix is given in Table 3.5. Here, the entries of the matrix are TFNs, (x, y, z), with lower bound x, middle value y, and upper bound z.

| Criterion 1 | Criterion 2 | Criterion 3 |
|--|--|-------------|
| (1,1,1) | (a, b, c) | (d, f, g) |
| (c ⁻¹ , b ⁻¹ , a ⁻¹) | (1, 1, 1) | (h, i, j) |
| (g ⁻¹ , f ⁻¹ , d ⁻¹) | (j ⁻¹ , i ⁻¹ , h ⁻¹) | (1, 1, 1) |

Table 3.5: Fuzzy Criteria Matrix

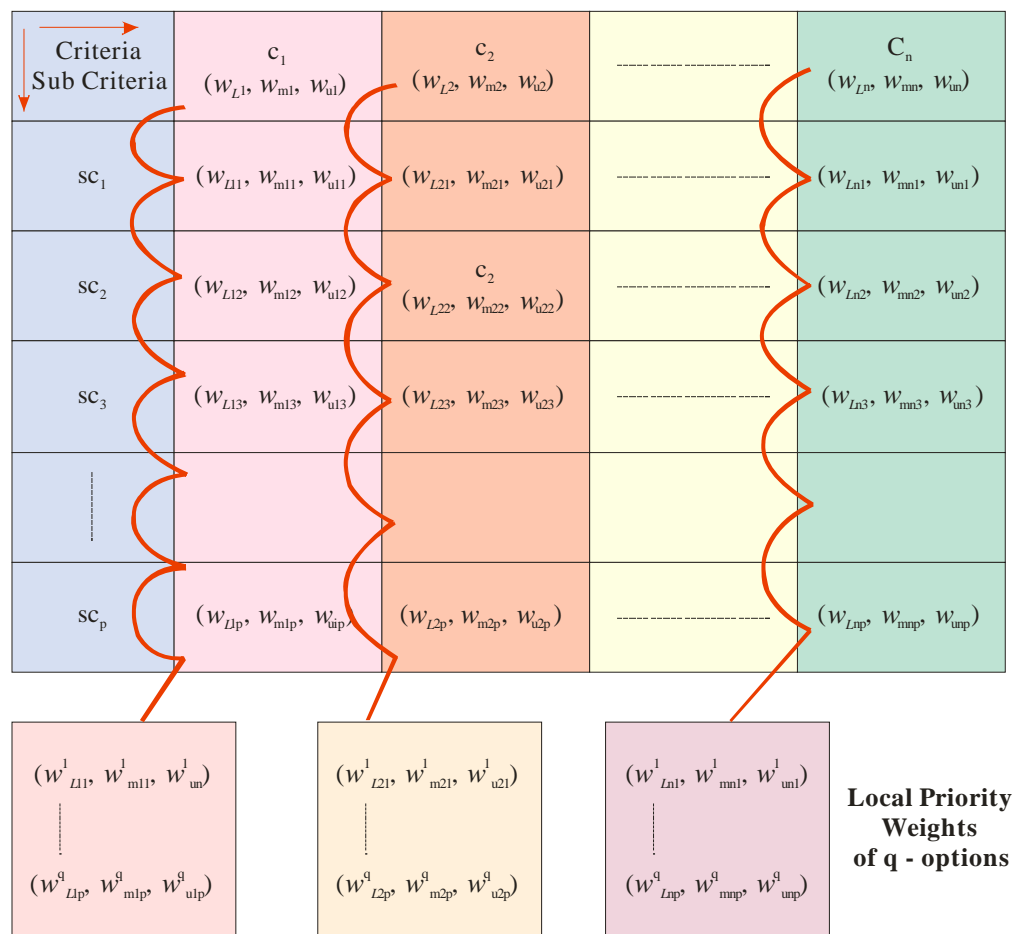
The other entries are chosen by reciprocity. The priority weights of criteria are obtained by the following procedure (Wang et al., 2008).

- a) For each row i , the row sum is calculated as a TFN, ($l_i =$ (sum of lower triplets), $m_i =$ (sum of middle triplets), $u_i =$ (sum of upper triplets)).
- b) The fuzzy priority weights of the criteria are computed using the following formula:

$$w_{ci} = \left(\frac{l_i}{l_i + \sum_{j=1, j \neq i}^k u_j}, \frac{m_i}{\sum_{j=1}^k m_j}, \frac{u_i}{u_i + \sum_{j=1, j \neq i}^k l_j} \right), \quad i = 1, \dots, k, \quad (3.23)$$

where c_i (in subscript) stands for the i -th criteria, and k is the total number of criteria in the entire analysis. Similarly, the fuzzy priority weights of associated sub-criteria and n options available in the AHP analysis are computed. These weights will also be TFNs.

- c) The fuzzy priority weights of criteria and the options are then aggregated to compute the absolute fuzzy weights. The aggregation rule is briefly presented in the following Figure : 3.7.



Fuzzy AHP Weight Aggregation

Figure 3.7: Aggregation of Priorities

In a three level hierarchy of fuzzy AHP, let there be n -criteria C_1, C_2, \dots, C_n at level 1, each criterion has p -sub-criteria SC_1, SC_2, \dots, SC_p at level 2, while there are q -options/alternatives to rank at third level since the local priority weights are fuzzy we

denote them by triplet with subscript (l, m, u) respectively. So, the i^{th} criterion priority weight is represented as (w_{li}, w_{mi}, w_{ui}) . Note that w_{mi} is the middle number of a TFN with membership value 1 while w_{li} is the left and w_{ui} is the right end points of the same TFN both having membership values zero. Similar interpretation is attached to the priority weights of the sub-criteria. For instance, the sub-criteria 1 of criteria 2 has priority weights as a TFN denoted by $(w_{l21}, w_{m21}, w_{u21})$. In general, the local priority weight of the j^{th} sub criterion of the i^{th} criterion is a TFN expressed as $(w_{lji}, w_{mji}, w_{uji})$. The local priority weights of the options are represented in a Figure: 3.7, in blocks. So the TFN representing the weight of the k^{th} option with respect to the j^{th} sub-criterion of the i^{th} criterion is denoted by $(w_{lji}^k, w_{mji}^k, w_{uji}^k)$.

In Figure 3.7, (w_{l1}, w_{m1}, w_{u1}) denotes the fuzzy priority weights of the first criterion, and $(w_{l11}, w_{m11}, w_{u11})$ denotes the fuzzy priority weights of the first option with respect to the first criterion calculated from the formula. Similarly we can interpret the other entries in Figure 3.7.

Table 3.6 shows the indexing of the fuzzy data. The indexing procedure is same as explained for AHP except that it now uses fuzzy arithmetic rules (Kaufmann and Gupta, 1991). For indexing the actual data, the middle element in the first cell of each row is regarded as the base and the rest of the elements in the row are divided by it to generate the ratio scales using the principle of fuzzy division.

| | | |
|---|---|---|
| $\frac{a_{11}}{b_{11}}, \frac{b_{11}}{b_{11}}, \frac{c_{11}}{b_{11}}$ | $\frac{a_{12}}{b_{11}}, \frac{b_{12}}{b_{11}}, \frac{c_{12}}{b_{11}}$ | $\frac{a_{13}}{b_{11}}, \frac{b_{13}}{b_{11}}, \frac{c_{13}}{b_{11}}$ |
| $\frac{a_{21}}{b_{21}}, \frac{b_{21}}{b_{21}}, \frac{c_{21}}{b_{21}}$ | $\frac{a_{22}}{b_{21}}, \frac{b_{22}}{b_{21}}, \frac{c_{22}}{b_{21}}$ | $\frac{a_{23}}{b_{21}}, \frac{b_{23}}{b_{21}}, \frac{c_{23}}{b_{21}}$ |
| $\frac{a_{31}}{b_{31}}, \frac{b_{31}}{b_{31}}, \frac{c_{31}}{b_{31}}$ | $\frac{a_{32}}{b_{31}}, \frac{b_{32}}{b_{31}}, \frac{c_{32}}{b_{31}}$ | $\frac{a_{33}}{b_{31}}, \frac{b_{33}}{b_{31}}, \frac{c_{33}}{b_{31}}$ |

Table 3.6: Fuzzy Division

Fuzzy multiplication between the indexed fuzzy data and the absolute fuzzy weights in Figure 3.7 is then carried out which produces a fuzzy weighted indexed matrix.

This fuzzy result thus obtained is subsequently defuzzified using the Centre of Gravity method for TFNs (Nasibov and Mert, 2007), that is, if (x, y, z) is the TFN, then its centre of gravity is given by

$$C_x = \frac{x+y+z}{3}. \quad (3.24)$$

The defuzzified Table finally assigns the ranks of the options just like in the crisp AHP analysis.

3.4. Conclusion

The methodologies described in this Chapter have been used to develop a software based decision support system (using Java programming language) for supporting sustainability related policy design. The decision support system comprises of three

software functionalities- Options vs Fuzzy Criteria, AHP and Fuzzy AHP. The description of the software system follows in the next Chapter.

CHAPTER 4: SOFTWARE DESCRIPTIONS

This Chapter provides details of the software functionalities (Options vs Fuzzy Criteria, Analytical Hierarchy Process and Fuzzy Analytical Hierarchy Process matrices) that have been developed as a part of the present research. Here the functionalities have been used to develop case study based models that consider regional sources of biofuels and demonstrates how these software functionalities can allow for sustainable biofuel production policy formulation.

4.1. Background on Software Compendium

In this research, an open source Java based Dialogue Mapping software, **Compendium** (Compendium Institute, 2002) is chosen as the benchmark software for capturing conflicting stakeholders' viewpoints. Compendium allows for enabling meeting and other communication to be linked together (Selvin et al. 2001) in an organised way through a visual interface. Conklin (2006) and Shum et al. (2006) identify the functional elements supported by Compendium hypermedia concept mapping, conceptual framework development, and meeting facilitation. Through hypermedia concept⁵ mapping, Compendium provides a visual view of issues, questions and ideas and the connections between them. Within the context of present analysis, specific extensions to Compendium are made, allowing for additional functionalities and enhanced decision-making capacity. The usefulness of Compendium is further augmented by addition of the Options vs Fuzzy Criteria

⁵ Compendium's hypermedia capabilities allows for providing the visual maps of concepts joined by semantic links, with multiple nodes representing the Issue being dealt with (Question), Arguments and Answers.

Matrix, Analytical Hierarchy Process matrix and the Fuzzy Analytical Hierarchy Process Matrix.

4.2. Software Design Rationale

The aim behind the development of the decision support system is to aid the stakeholders in the decision-making process. For this purpose, the software has developed an extensive Graphical User Interface (GUI) for ease of use. Essentially for the overall working of the software, a data have to be retrieved from the data store and displayed for the user. After the user changes the data, the system stores the updates in the data store. This type of a software design rationale is known as the Model-View-Controller (MVC) design pattern.

User interface logic tends to change more frequently than business logic, that is, the instance when data are input by the users may change frequently, whereas the underlying methodology (discussed in the previous Chapter) remains constant. Hence, there is a need to keep the presentation code (for the purpose of displaying the GUI) and the business logic code separate. This is the purpose of MVC, a fundamental design pattern for the separation of user interface logic from business logic. This is shown in Figure 4.1 which displays three components of the MVC design pattern:

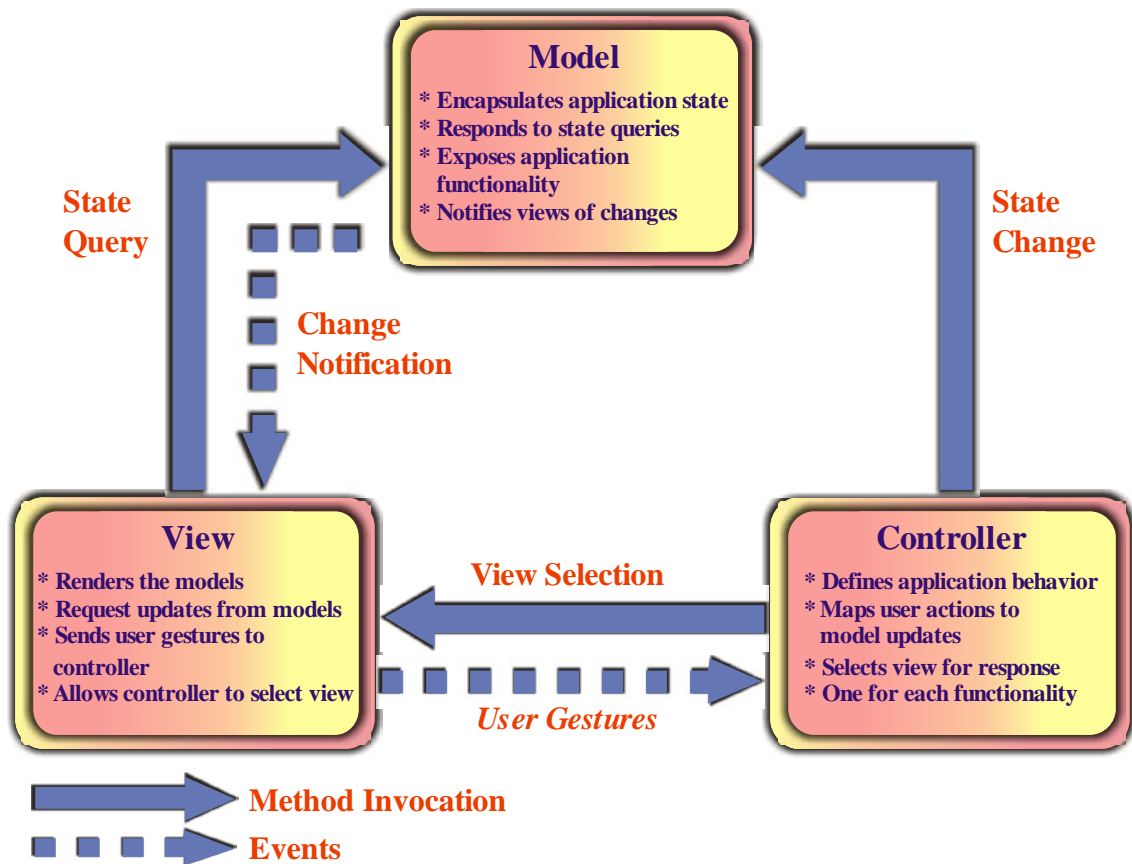


Figure 4.1: Model View Controller (MVC) Design Pattern
(Sun Microsystems, 2002)

Model - The model serves as a software approximation to a real-world process, so simple real-world modelling techniques apply when defining the model. For example, the present case the Model comprises the methodology described in Chapter 3.

View -The view renders the contents of a model. It accesses enterprise data through the model and specifies how those data should be presented. It is the view's responsibility to maintain consistency in its presentation when the model changes. This can be achieved by using a push model, where the view registers itself with the

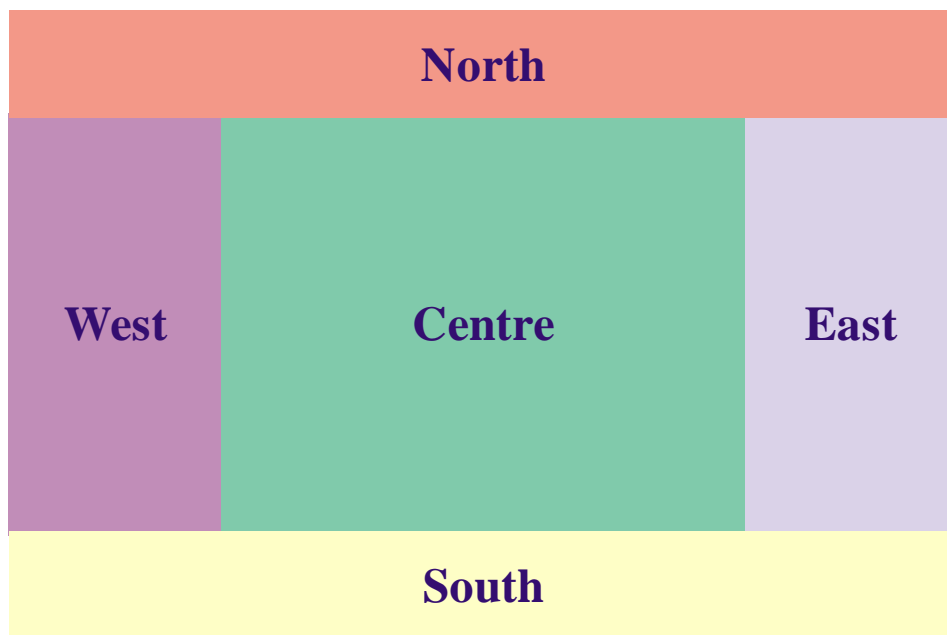
model for change notifications, or a pull model, where the view is responsible for calling the model when it needs to retrieve the most current data.

Controller - The controller translates interactions with the view into actions to be performed by the model. In a stand-alone GUI client, user interactions could be button clicks or menu selections. The actions performed by the model include activating business processes or changing the state of the model. Based on the user interactions and the outcome of the model actions, the controller responds by selecting an appropriate view.

In order to create the GUIs of the software functionalities, the author has used a variety of layout managers provided by Java Swing have been used to allow for the placement of buttons, text fields etc at their exact locations. The common layout managers are BorderLayout, GridLayout and FlowLayout. Layout managers have been nested to produce the desired layouts.

The BorderLayout splits a container into five sections: north, south, east, west and centre, as shown in Figure 4.2.

Elements can be added to any of the areas available. This layout provides the user with a good starting point for designing how a GUI will look and allows elements to be placed accurately on the screen.



**Figure 4.2 Border Layout showing the Sections available
(Sun Microsystems, 2005)**

There are some points to consider when using a BorderLayout in terms of the preferred size of the five components it holds. North and South – where possible the height of these components is set to their preferred height. The width is set to the width of the container. East and West – where possible the width of these components is set to their preferred width. The height is set to the remaining height available. Centre – this fills any remaining space available and in our case houses the JTables- the GUI of the Tables which displays the data.

In a Flow Layout components (such as buttons in this case) are added in order from left to right. The default is to centre them in the container but this can be changed to align them to the left or the right if required. If the addition of more components goes beyond the width of the container then the components are added on a new line.

The Grid Layout class is a layout manager that lays out a container's components in a rectangular grid. The container is divided into equal-sized rectangles, and one component is placed in each rectangle. A GridLayout object places components in a grid of cells. Each component takes all the available space within its cell, and each cell is exactly the same size. If the GUI window is resized, the GridLayout object changes the cell size so that the cells are as large as possible, given the space available to the container.

For the design of the software functionalities, the author designed the Model to serve the purpose of representing the methodology and business rules that govern access to and updates of this data. The Model aims to serve as a software approximation to a real-world process or methodologies (such as those described in the previous Chapter). It stores and retrieves the data for display by the GUI. Any changes made to the GUI are recorded by the model and it notifies the View of changes (Java BluePrints).

The controller translates interactions with the view into actions to be performed by the model. In a stand-alone GUI client, user interactions could be button clicks or menu selections. It interprets the mouse and keyboard inputs from the user, informing the model and/or the view to change as appropriate. The controllers and the model communicate with the view via *events*. Events provide nicely de-coupled mechanisms that allow communication, with minimal dependencies.

Using the graphical components' "list box", an "entry field" or "radio buttons" as examples, these view components will receive event notifications such as *needs contents*, or *clicked*. The events will often come from the controller. The application

model knows that it might have views, and it knows that those views will be dependent on it. So whenever an aspect of the model changes, the application model triggers an event via the controllers to update the View (Deacon, 2005).

This design pattern has been used to develop all the three software functionalities developed as a part of this research.

4.3. Options vs Fuzzy Criteria Matrix

The Options vs Fuzzy Criteria matrix is much enhanced in its scope compared to the older functionality, Options vs Criteria Matrix (developed by Simon Skrzypczak, 2007). In the older functionality, the scope of the criterion was limited to criterion name and the value/formula related to the criterion name. However, in the Options vs Fuzzy Criteria matrix, the scope of criterion has been enhanced by the author such that in addition to specifying the criterion name it is possible to specify whether the criterion is fuzzy or not and if it is so, the linguistic variables associated with it can be specified. These linguistic variables are stored in form of constant values (VERY LOW, LOW, MEDIUM, HIGH and VERY HIGH). The upper and lower bounds of the linguistic variables can be specified too as shown in Figure 4.3.

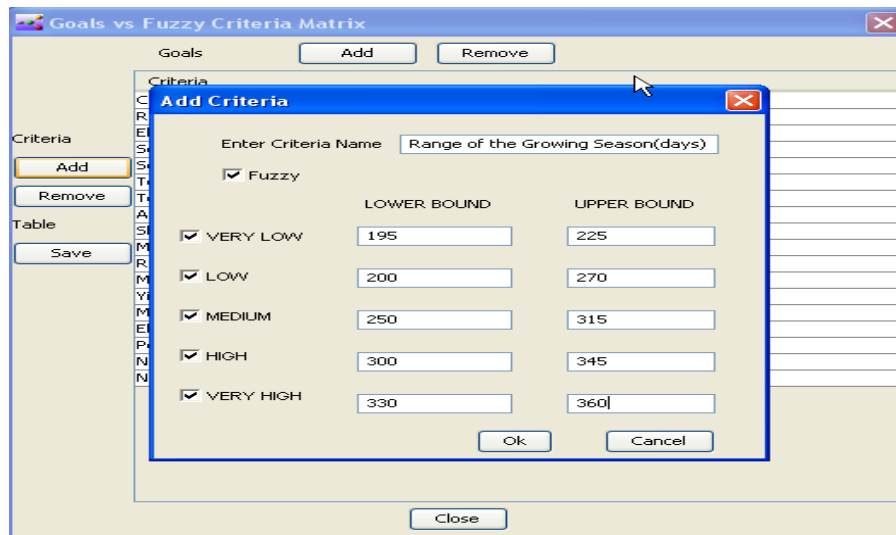


Figure 4.3: Specifying a Criterion as Fuzzy

It can be seen from Figure 4.3 that the boundaries of the linguistic variables that describe the fuzzy criterion overlap. This is a distinct advantage of fuzzy logic that it provides the conceptual basis for dealing with uncertainty arising out of imprecise boundaries between various different categories (McBratney and Odeh, 1997). Owing to the requirements of the Options vs Fuzzy Criteria matrix, the scope of the default JTable GUI has been extended by the author to support combo boxes within the matrix cells and the colouring of the cells which are dealing with fuzzy criteria (in order to distinguish them from the non fuzzy criteria). This was not so in the older functionality.

The implementation of the Options vs Fuzzy Criteria matrix in Compendium requires interaction with the existing Compendium software in order to work. The Options vs Fuzzy Criteria matrix should be available for every issue node in a Compendium project, and therefore the system needs to know when it encounters an issue node. The Options vs Fuzzy Criteria matrix itself is reliant on two ancillary Tables/matrices to function correctly. The first of these is the Global Parameters Table (retained from

Skrzypczak, 2007). Global parameter refers to the parameters whose values are stored in the global parameters Table and parameters themselves can be referenced from the matrix. The second Table is the Goals vs Fuzzy Criteria matrix (adapted from the Goals vs Criteria Matrix developed by Skrzypczak, 2007), which holds details of all the criteria (both fuzzy and non fuzzy) available to a project. This functionality is incorporated into Compendium as a tabbed pane which displays the Options vs Fuzzy Criteria matrix for an issue node. Figure 4.4 shows how information flows between each of the components that make up the functionality.

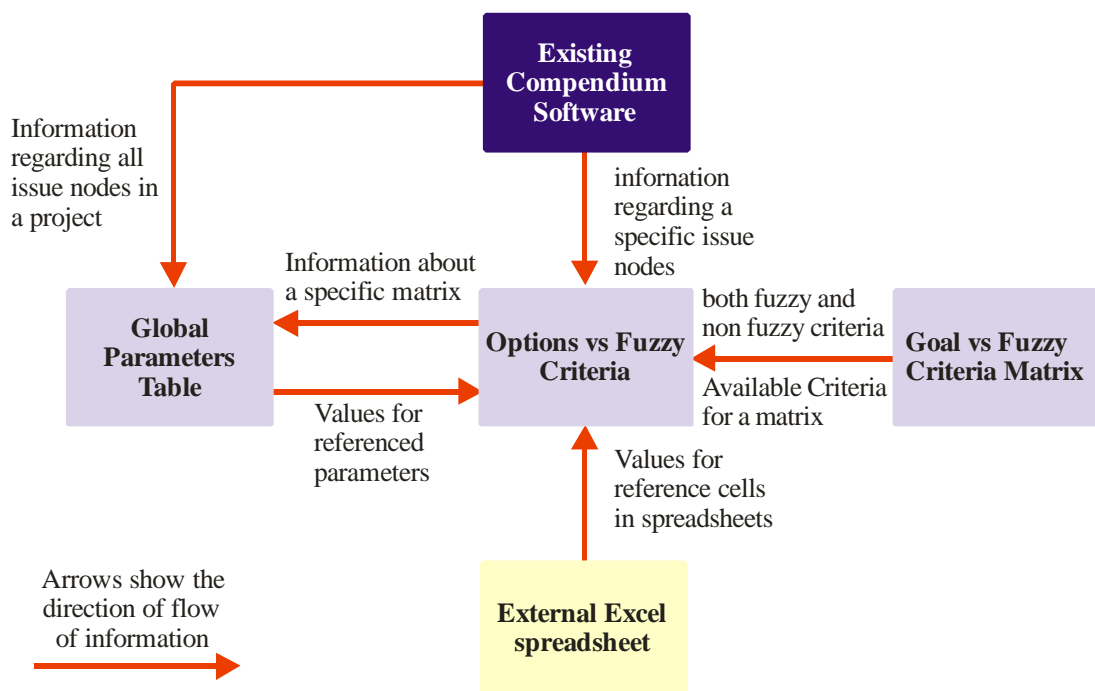


Figure 4.4: Information Flow across the Options vs Fuzzy Criteria Matrix (Adapted from Skrzypczak, 2007)

This functionality has a further provision of performing a sensitivity analysis on the fuzzy criteria using linguistic variables. The value of the selected (fuzzy) criterion is varied between a set of linguistic variables to see the impact on the recommendation of options.

4.4. AHP Functionality

In literature, Dialogue Mapping is used in conjugation with other analytic and facilitation approaches like the AHP in order to provide decision support for stakeholders (Conklin, 2006). This theoretical concept is turned into implementation by the addition of the AHP functionality into the existing Dialogue Mapping software, Compendium.

This functionality is incorporated into Compendium by the author as a tabbed pane which displays the Analytical Hierarchy Process matrix for an issue node. Like its predecessor, the implementation of the AHP functionality in Compendium requires interaction with the existing Compendium software in order to work. The AHP matrix should be available for every issue node in a Compendium project. The Goals vs Criteria Matrix of the older functionality (Options vs Criteria Matrix, developed by Skrzypczak, 2007) has been retained. This allows for addition of criteria within the AHP functionality. The information flow between the various components of the AHP software functionality is described in Figure 4.5.

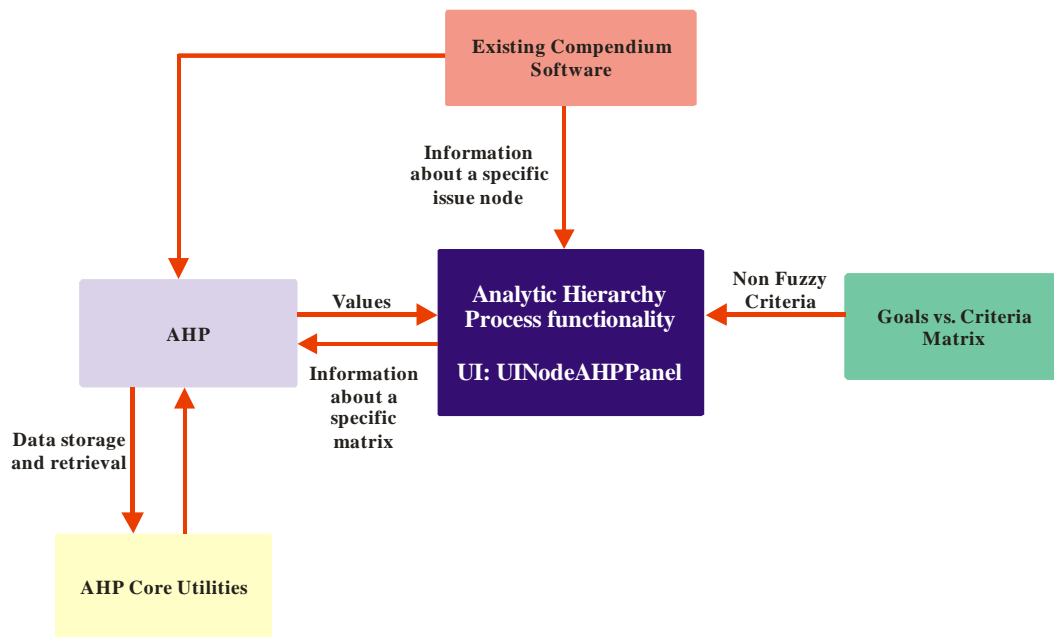
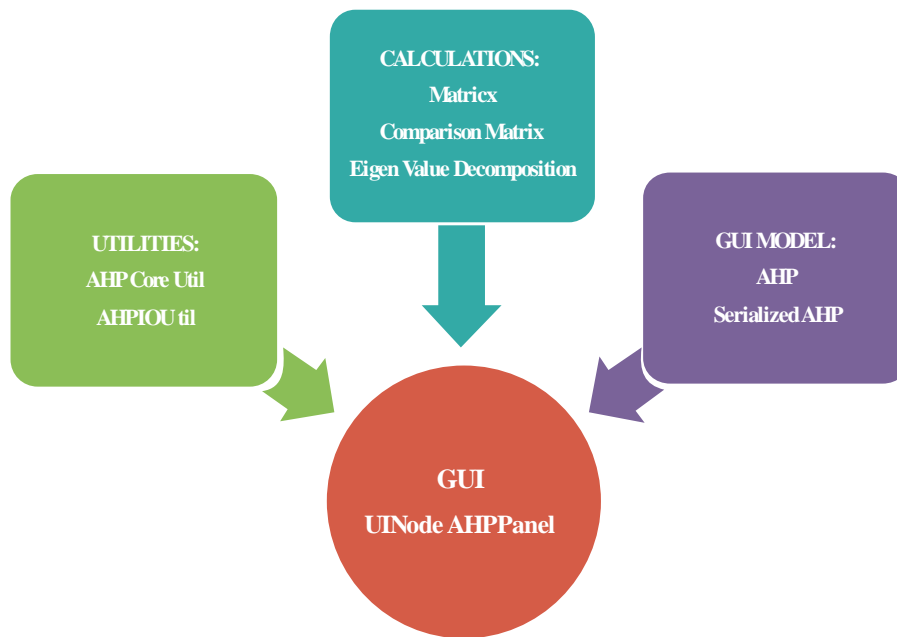


Figure 4.5: Information Flow across the Analytical Hierarchy Process Functionality (Adapted from Skrzypczak, 2007)

The Analytical Hierarchy Process matrix is dependent on two key user defined classes for its functionality. These are the UINodeAHPPanel and the AHP classes respectively. The UINodeAHPPanel is responsible for creating the User Interface of the functionality, that is, the part of the software functionality which interacts with the user and AHPCoreUtilities allows for saving data. Author has designed the UINodeAHPPanel to allow the user to enter n criteria which are relevant to the issue under consideration. The $n \times n$ criteria matrix is thus generated. The names of the criteria and the corresponding data Table are stored by the variables *criteriaList* and *criteriaDataModel* respectively.

Apart from these two, all the classes of the AHP have different purposes and interact in the following way:



**Figure 4.6: Interaction among the Analytical Hierarchy Process
Functionality classes**

There is a further scope of assigning sub-criteria to each of criterion. Assignment of sub-criteria to their respective criteria makes use of a HashTable⁶ (known as the subCriteriaMap) which holds mapping of Criteria and their respective sub-criteria in the form of key -value pairs. The storage of the criteria and associated sub criteria structure is supported by another HashTable, *subCriteriaDataModel* which holds mapping of Criteria and data models⁷ of their respective sub-criteria in the form of key -value pair. The mapping of the sub criteria with the options is managed by optionDataModel which is a HashTable holds mapping of sub-criteria and data

⁶ HashTable is a data structure that maps certain identifiers/keys to associated values. In this case, the criteria names acts as the key and the associated sub criteria act as the values.

⁷ A data model acts as the Model (stores and retrieves information) displayed in a given JTable. In this case, each sub-criteria has a JTable assigned to it which displays the preference information input by the user. This information is stored by the data model.

models of their respective options in the form of key -value pair, where key is criteria (restricted to String⁸), and value is a data model⁹ of their options.

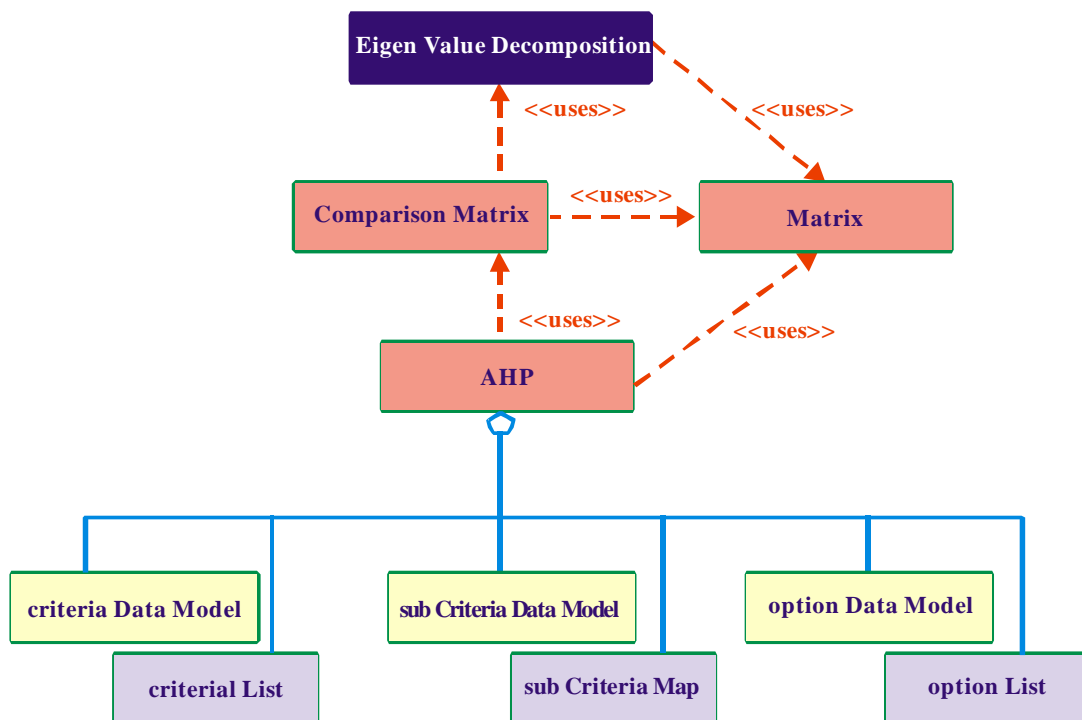


Figure 4.7: Components of the Analytical Hierarchy Process Functionality

The GUI is provided by the class UINodeAHPPanel which allows the number of criteria, sub-criteria and options associated with the given issue node to be added and removed dynamically, with the help of command buttons and can be viewed in tabbed panes (whose provision is provided for by the Java Swing component JTabbedPane). Thus to keep a track, two vectors¹⁰ (known as criteriaList and optionList) both restricted to Strings are made to handle criteria list and option list, which holds the collection of all criteria names and options respectively, related to the given issue

⁸ In computer programming, String is a sequence of characters.

⁹ Is an abstract model that represents how data are represented and accessed.

¹⁰ The Vector class in Java implements a growable array of objects. Like an array, it contains components that can be accessed using an integer index. However, the size of a Vector can grow or shrink as needed to accommodate adding and removing items after the Vector has been created.

node. The GUI also provides JTables¹¹ to capture the input from the user for all the criteria, sub-criteria and options associated with the issue node. While the input is provided in the JTables by the user, the DataTableModels are working behind the scenes to capture and hold that data, before it is permanently stored in serialized object format.

Capturing of criteria values is done in a DefaultTableModel¹², which captures the value of the cells of JTable.

A tabbed pane for each of the sub-criteria is generated which in turn is populated by the options associated with the issue. This can be viewed by pressing the “View Options” button which displays a new GUI. The “View Options” button act as a toggle button, so that the user can easily switch between two views namely “Criteria View” and “Options View”. Once clicked the “View Options” button opens up the options view and the caption of the button changes to “View Criteria”. If clicked again, it reverts back to criteria view, and so does the captions too reverts back to “View Options”.

The entries of the criteria and options matrices can be entered using a slider based on the 1-9 Saaty’s scale. Reciprocacity is maintained by default. The pairwise comparisons entered by the users are copied into a matrix called ‘crit’ which is the instance of the class ComparisonMatrix. The Comparison Matrix class is used for

¹¹ The JTable is used to display and edit regular two-dimensional Tables of cells

¹² As per [the Swing Architecture](#) and MVC design pattern, model classes and/or interfaces provide and manipulate the data displayed in the UI components (View + Control). [DefaultTableModel](#) is the model classes that can be used to populate the view [JTable](#).

calculation of a number of functions associated with the AHP Methodology such as consistency ratio, consistency index and priority weights. For this purpose it makes use of the class EigenValueDecomposition which supports the calculation of the eigenvectors of a real matrix and the maximum priority vector (λ_{\max} which is used for the calculation of consistency index). The matrix allows the 2D arrays to be represented in the form of a user defined data type matrix such that the matrix calculations (supported by EigenValueDecomposition) may be carried out.

Using the functionality of these classes, the priority weights are obtained which in turn are multiplied by the data values of the indexed/graded data model.

The AHP class is further supported by the AHPCoreUtilities class which allows for data storage and data retrieval. Data storage has been carried out by Java serialization. Object serialization is the process of saving an object's state to a sequence of bytes, as well as the process of rebuilding those bytes into a live object at some future time. The Java Serialization API¹³ provides a standard mechanism for developers to handle object serialization. An object is marked serializable by implementing the java.io.Serializable interface, which signifies to the underlying API that the object can be flattened into bytes and subsequently inflated in the future.

Subsequently the data is entered and if needed, it may be graded by the users; indexing is done by default prior to rank calculation. The AHP class computes and aggregates the eigenvectors/priority vectors in order to obtain the composite absolute

¹³ API stands for Application Programming Interface. The Java API provides mechanism for object serialization (Greanier, 2000).

weight for the options/alternatives (shown in Figure 4.7). Then the indexed data is multiplied by the absolute weight to obtain the overall weight coefficient of each of the options (Pohekar and Ramachandran, 2004). Based on these, the ranking of the options is obtained in the descending order. A provision for sensitivity analysis has been provided within the functionality itself which allows for seeing the impact of varying the criteria preference (represented in terms of criteria weights) on the recommendation of suitable options.

Within the framework of the AHP software functionality, both factual data and stakeholder preferences (in form of pairwise comparisons) are incorporated in order to allow for the recommendation of possible options and policies which may help achieve the desired future sustainability goal. This functionality has been further augmented by the incorporation of fuzzy set theory to form the Fuzzy AHP functionality.

4.5. Fuzzy AHP Functionality

The Goals vs Criteria Matrix of the functionality Options vs Criteria Matrix (developed by Skrzypczak, 2007) has been retained. This allows for addition of criteria within the Fuzzy AHP functionality. The information flow between the various components of the Fuzzy AHP software functionality has been described in Figure 4.8:

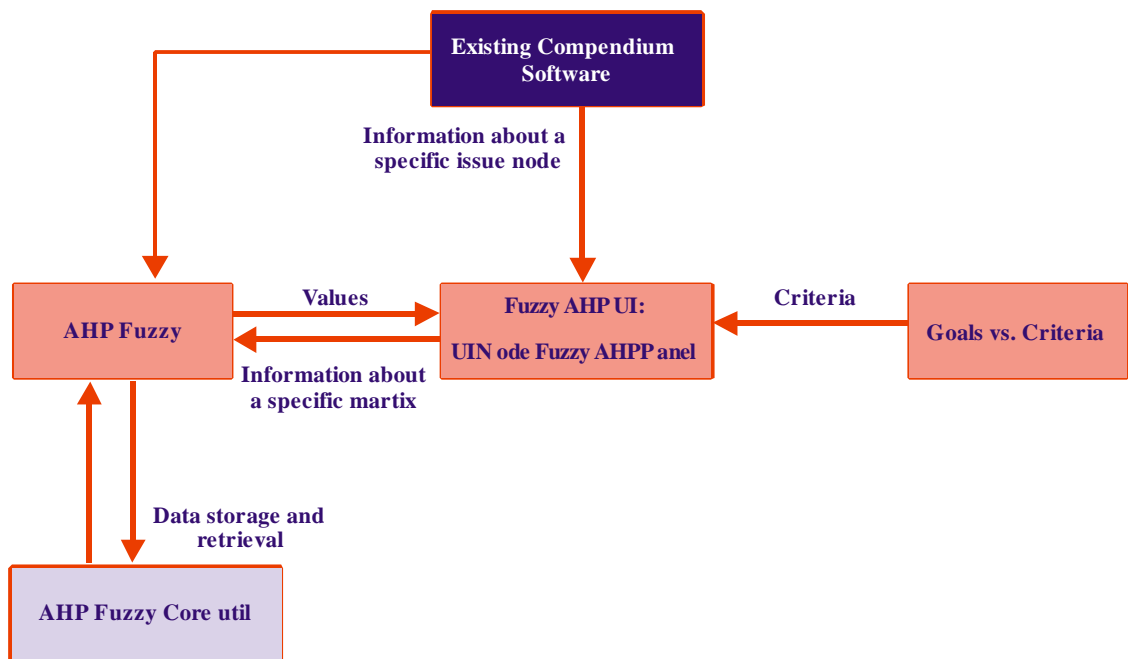
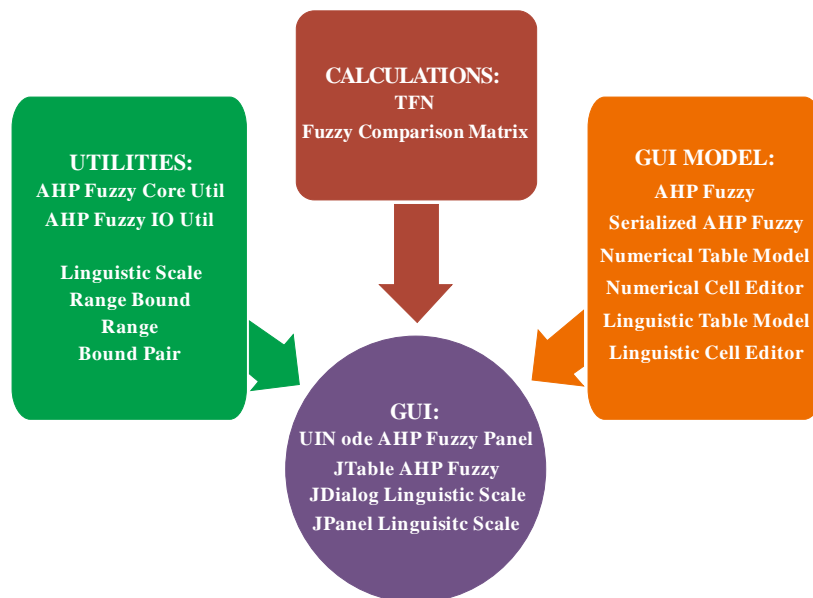


Figure 4.8: Information Flow across the Fuzzy Analytical Hierarchy Process Functionality (Adapted from Skrzypczak, 2007)

The Fuzzy Analytical Hierarchy Process matrix is dependent on two key user defined classes for its functionality. These are the UINode AHP Fuzzy Panel and the AHPFuzzy classes respectively. The UINode AHP Fuzzy Panel is responsible for creating the User Interface of the functionality, that is, the part of the software functionality which interacts with the user. It allows the user to enter n criteria which are relevant to the issue under consideration. The nxn criteria matrix is thus generated. Simultaneously, a tabbed pane for each of the criteria is generated which in turn is populated by the options associated with the issue. The entries of the criteria and options matrices can be entered using a slider based on a fuzzy preference scale (Table 3.3) From the slider, the user chooses the relevant linguistic variable to describe the preference. The value of the linguistic variables lies between a lower and upper bound. When this value is set into the matrix; it is automatically converted to a TFN (triangular fuzzy number). Reciprocity in the comparison matrix is maintained

by default. The AHP Fuzzy class computes and aggregates the fuzzy eigenvectors/priority vectors in order to obtain the composite absolute weight for the options/alternatives. Then the indexed data is multiplied by the absolute weight to obtain the overall weight coefficient of each of the options (Pohekar and Ramachandran, 2004). Defuzzification is carried out and the ranking of the options is obtained in the descending order. The AHP class is further supported by a number of other classes including the AHPCoreUtilities class which allows for data storage and data retrieval. Figure 4.9 shows the interactions between the different classes:



**Figure 4.9: Interaction among the Fuzzy Analytical Hierarchy Process
Functionality classes**

The GUI is provided by the class UINode AHP Fuzzy Panel which allows the number of criteria, sub-criteria and options associated with the given issue node to be added and removed dynamically, with the help of command buttons and can be viewed in JTabbedPanes. Thus to keep a track criteria List and option List restricted to strings are made to handle criteria list and option list. Assignment of sub-criteria to their

respective criteria makes use of a HashTable which holds mapping of criteria and their respective sub-criteria in the form of key -value pair .

The GUI also provides JTables to capture the input from the user for all the criteria, sub-criteria and options associated with the issue node. While the input is provided in the JTables by the user, the Data Table Models are working behind the scenes to capture and hold that data, before it is permanently stored in serialized object format to storage location.

Capturing of criteria values is done in a Default Table Model, which captures the value of the cells of JTable. Capturing of sub-criteria and options is done in two HashTables (known as the sub Criteria Data Model and option Data Model respectively) which holds the values of Sub-Criteria and Options respectively, in the form of key -value pair, where key (restricted to strings) is the unique criteria name, and value is a Default Table Model which captures the value of the cells of JTable.

The data can be entered into the data matrix both using a numerical matrix (where the TFNs have to be entered manually) and a linguistic matrix for which the user specifies the linguistic value and the range for each cell using a dialog box. This is achieved by using two different Table models for the same data Table (created in class JTableAHPFuzzy) - a numerical Table model and a linguistic Table model. The interaction of the numerical and linguistic Table view is illustrated in Figure 4.10.

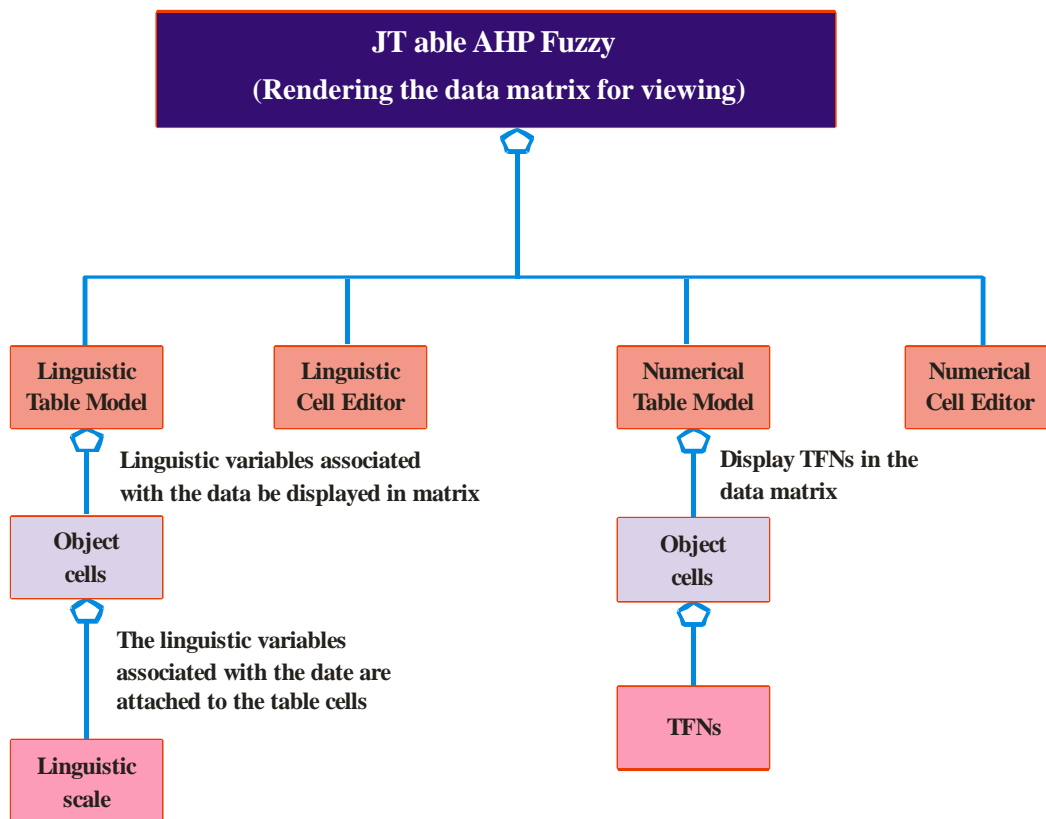


Figure 4.10: Creation of a Customized Table GUI for Displaying Data Both in Linguistic and Numerical Form

The user can shift between these two models using radio buttons. For both these models, the editing mode of the data is different thereby requiring the usage of different cell editors. For the numerical Table model, an input box (a text field) accepts values from the user. For the linguistic Table model, a dialog box is used to input the value- linguistic variable and the associated numerical values into the input text field. The linguistic variables that the user can use to describe the data values have been defined in a class called LinguisticScale. LinguisticScale stores the linguistic variables {VERY LOW, LOW, MEDIUM, HIGH, VERY HIGH} that may be associated with the data value and provides provision for storing the range of values associated with the linguistic variable. A provision for sensitivity analysis has been provided within the functionality itself which allows for seeing the impact of

varying the fuzzy criteria preference (represented in terms of criteria fuzzy priority weights) on the recommendation of suitable options.

In conclusion, the Fuzzy AHP methodology, both in theory and practise, combines the distinct features of both AHP and fuzzy logic to allow for estimate preference comparisons for the criteria and alternatives in terms of linguistic variables. Like the AHP functionality, it provides support for playing out the possibilities of the given decision policies and examining their long term effects.

In context of the aims of the research, the software decision support can be used to provide insight not only into the performance of each of the sustainability options within the current regional constraints but also help identify sustainability options and formulate policies over a pre-established time frame. However, the most vital benefit of the software stems from the fact that it can be used by decision makers coming from variety of backgrounds and do not possess either programming skills or in depth knowledge of the concepts of fuzzy logic and MCDM utilized for software development.

CHAPTER 5: OPTIONS VS FUZZY CRITERIA MATRIX

This Chapter provides an illustration of how linguistic uncertainties may be mathematically used within a decision-making process. In order to incorporate linguistic uncertainties within the decision-making process, software functionality Options vs Fuzzy Criteria has been developed. A case study, pertaining to land resource usage has been performed in order to demonstrate the working of the Options vs Fuzzy Criteria Matrix functionality and its efficacy in handling ambiguous inputs and giving concrete answers to problems fraught with subjectivity.

The motivation behind the selection of the specific issues tackled in the Chapter stems from the fact that selection of a suitable land type is required for sustainably growing crops dedicated to biofuel production selection (Tenerelli and Monteleone, 2008). During the course of research it was realized that the data pertaining to land resource usage in the Philippines which the present case study is based on, is characterized by imprecise information and overlapping data boundaries. Therefore the Options vs Fuzzy Criteria matrix was selected which allows for the inclusion of both linguistic terms and overlapping data boundaries in the decision-making process.

5.1. Land Resource Management

The case study set in the Philippines is used to illustrate the concepts discussed above and the working of the functionality. Data for this study can be found in Appendix 1. The data are adapted from the Land Capability Classification developed by the Bureau of Soils and Water Management of the Philippine government whereby different types of land are categorized according to soil types and slope categories

(FAO, 2001). According to this, 9 separate land options are used to classify the area (Class X land, Class N land etc). These options will be compared against different weighted criteria. These criteria are: range of the growing season, elevation, soil depth, severity of soil erosion (or the number of gullies) and the topographic slope criteria (Venkateswarlu, 2001). The criteria are used to evaluate the 9 land resource options. The criteria are described using linguistic expressions and are shown in green in Figure 5.1.

| Criteria | Class X | Class N | Class Y | Class L | Class B | Class M | Class A | Class D | Class C | Weight | Normalisa... |
|-------------------------------|-----------|-----------|-----------|----------|-------------|---------|-----------|----------|----------|--------|--------------|
| Range of the Growing S... | VERY LOW | VERY LOW | VERY LOW | MEDIUM | VERY HIGH | LOW | VERY HIGH | MEDIUM | HIGH | 9 | 0.0028 |
| Elevation | MEDIUM | HIGH | VERY HIGH | MEDIUM | LOW | HIGH | LOW | MEDIUM | MEDIUM | 2 | 0.002 |
| Topography Slope | VERY LOW | LOW | VERY LOW | MEDIUM | HIGH | LOW | HIGH | MEDIUM | MEDIUM | 3 | 0.0333 |
| Soil Depth | VERY LOW | LOW | VERY LOW | MEDIUM | VERY HIGH | LOW | VERY HIGH | HIGH | HIGH | 2 | 0.01 |
| Severity of soil erosion(...) | 74 | 24 | 74 | 14 | 11 | 24 | 9 | 14 | 4 | 2.5 | 0.0135 |
| Topographic Slope | VERY LOW | VERY HIGH | MEDIUM | VERY LOW | VERY LOW | HIGH | VERY LOW | VERY LOW | VERY LOW | 1 | 0.0303 |
| Temperature Regimes | VERY HIGH | MEDIUM | HIGH | MEDIUM | VERY HIGH | HIGH | VERY HIGH | MEDIUM | MEDIUM | 1 | 0.04 |
| Percentage Humus | VERY LOW | LOW | VERY LOW | MEDIUM | VERY HIGH | LOW | VERY HIGH | HIGH | HIGH | 1 | 0.1111 |
| Totals | 10.388 | 11.7358 | 11.8916 | 13.0039 | 16.2489 | 12.5806 | 16.2152 | 13.9761 | 14.9336 | | |
| System Recommended Decision | | | | | Recommended | | | | | | |

Figure 5.1: Options vs Fuzzy Criteria Matrix for Land Resources Evaluation

After carrying out the five steps described in Chapter 3, the system recommends “Class B” type soil land (classified as good quality agricultural land) for cultivating biofuel crops (see, Figure 5.1). However, use of good quality agricultural land for biofuel crop cultivation will divert the scarce arable land away from the cultivation of food crops, which may in turn raise concerns pertaining to food security (Boddiger, 2007). Hence, the decision-makers may have to consider other soil options. A provision for sensitivity analysis that has been provided within the functionality to enables this.

5.2. Performing Sensitivity Analysis on Fuzzy Criterion

In general, the purpose of sensitivity analysis is to assess the sensitivity of a model towards change in the input parameter hence allowing the user to evaluate the robustness of a particular decision or selected option.



Figure 5.2: GUI of the Sensitivity Analysis of Fuzzy Criteria

Here an improvement of the Options vs Fuzzy Criteria Matrix over Options vs Criteria Matrix can be clearly witnessed. The sensitivity analysis is performed using the linguistic variables rather than the numeric. An analysis shown in Figure 5.2 is performed to see the change in recommended option when one of the fuzzy criterion, “Length of Growing Season” is varied from VERY LOW to VERY HIGH. Usage of Class Y type soil land (marginal land with poor quality unfertile soil) is now recommended. Use of marginal land for biofuel cultivation instead of good quality agriculturally active land can potentially prevent biofuels from adversely affecting food security (Phalan, 2009).

5.3. Conclusion

This Chapter explored the efficacy of using linguistic variables, which in turn are supported by fuzzy numbers within a decision matrix. Even though the usage of the functionality, Options vs Fuzzy Criteria Matrix, has been demonstrated through specific case study pertaining to the land selection for biofuel production in the Philippines, the functionality has the flexibility to provide decision support for a wide spectrum of analogous decision making problems characterized by the presence of linguistic variables and imprecise boundaries between them.

Meanwhile, it is reasonably easy to realize the limitations of the proposed methodology. Options vs Fuzzy Criteria Matrix is deficient in its capabilities and realistic projections of performance of policy strategies for sustainable biofuel production. This Chapter stops short of exploring the full dynamics of fuzzy set theory. This is discussed in Chapter 6 which gives a more rigorous theory of fuzzy sets and their application in mapping a suitable crop onto the desired geographical region.

Chapter 6: Evaluating Land for Crop Cultivation Using Fuzzy Logic

The focus of this Chapter is to introduce fuzzy set theory and build a fuzzy mathematical model to pinpoint suitable geographical zones for cultivation of biofuel crops.

Recent years have seen a widespread interest in biofuels crops as a solution to the world's energy needs, particularly in light of concerns over greenhouse-gas emissions. Biofuel crops continue to be promoted and planted worldwide. But, there many pressing issues related to biofuel production, such as the potential invasion of plant species and problems of diverting arable land from food crop cultivation (which may endanger food security). Despite this, planting of biofuel crops continues to remain largely unregulated. The significance of the present study can be seen in this context wherein we attempted to build a model, based on fuzzy logic, which can provide support to identify potential site for growing the selected biofuel crop.

The decision making process related to sustainability such as the one undertaken in the present study is subjective. In order to build an appropriate model that can represent the problem adequately, we make use of the fuzzy set theory.

6.1. Study Area

The study area is the Philippines for which the geographical options are defined in terms of agro-ecological systems or Pedo Ecological Zones (PEZs) of the Philippines. The PEZ are broad ecological resource management regions classified on the basis of

geographical factors such as elevation, slope and temperature (Land Resources Information Systems in Asia, 2000). The classification includes three PEZ options, namely: Warm Lowlands, Warm-Cool Uplands and Cool Highlands.

PEZ, like most other systems in the real world, can be quantified in terms of linguistic descriptors that in turn can be linked to numerical information. The linguistic descriptors make use of linguistic variables while describing the features of a given system. In the present case, the features of the agro-ecological system such as Elevation, Slope and Temperature have been described in linguistic terms LOW, MEDIUM, and HIGH that have overlapping membership functions. The case study illustrates how fuzzy logic can fruitfully be used to determine the optimum potential region (PEZ) for cultivating a given crop from a geographical perspective among the various suitable regions in the Philippines. As already pointed out, selection of a suitable region is important before embarking on biofuel crop cultivation as the benefits and constraints offered by a given agro-ecological zone greatly impact the dynamics of agricultural production of the relevant agro-ecologically feasible cropping activities (Land Resources Information Systems in Asia, 2000).

The membership functions of PEZs are described by TFN's (Triangular Fuzzy Numbers¹⁴). The TFN's used for expressing the linguistic characterizations of each PEZ are extracted from the data range of criteria, namely elevation, slope and temperature that constitute these zones. The interval range $[x, y]$ for each PEZ and each criterion within it is converted to the symmetric TFN as $[x, z, y]$, where z is taken as the midpoint of x and y . It is computationally advantageous to read the

¹⁴ Triangular Fuzzy Numbers are used to describe the values of criteria between a range of values $[a, b, c]$ where a is the lowest possible value, c the highest possible value and b is the most probable value.

membership value of the crop C fuzzy data from the membership graphs of the PEZ, TFN's.

Table 6.1 lists the data describing the three salient features of the three PEZ of the Philippines :

| PEZ ↓ | ELEVATION | SLOPE | TEMPERATURE |
|----------------------|----------------------------|--------------------------|---|
| Warm Lowlands | LOW (0-110m) | LOW (0-8%) | HIGH ($>25^{\circ}\text{C}$) |
| Warm Cool Uplands | MEDIUM (100-550m) | MEDIUM (0-18%) | MEDIUM (22°C - 27°C) |
| Cool Highlands | HIGH ($>500\text{m}$) | VERY HIGH ($>33\%$) | LOW (17°C - 24°C) |

Table 6.1: Data of Criteria Characterizing the PEZ (FAO, 2001)

It can be observed that data describing elevation, slope, and temperature of a zone are not crisp but instead vary in certain ranges; thus they can be more appropriately modelled by linguistic expressions. Herein, the method of multifeature pattern recognition (see Section 3.2) is applied to this system with several fuzzy features, and the approaching degree concept is used to compare each new data pattern (in this case, it is the crop) with some known data patterns (those of the PEZ).

6.2. Selection of a Suitable Geographical Region for a Given Crop

The membership functions of the linguistic variables describing the criteria related to elevation, slope, and temperature have been derived from the fuzzy data presented in Table 6.1. The membership functions are taken as symmetric TFNs, with three control points taken respectively as the lower end of the data range, midpoint of the data

range, and the upper end point of the data range. The triangular fuzzy membership functions are illustrated in Figures 6.1(a) to 6.1(c).

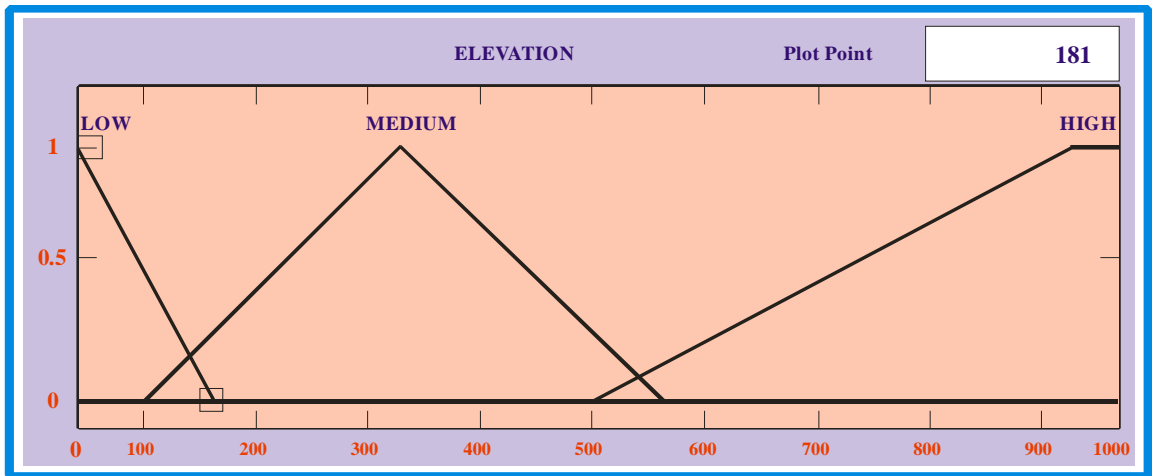


Figure 6.1a: Membership Functions of Elevation

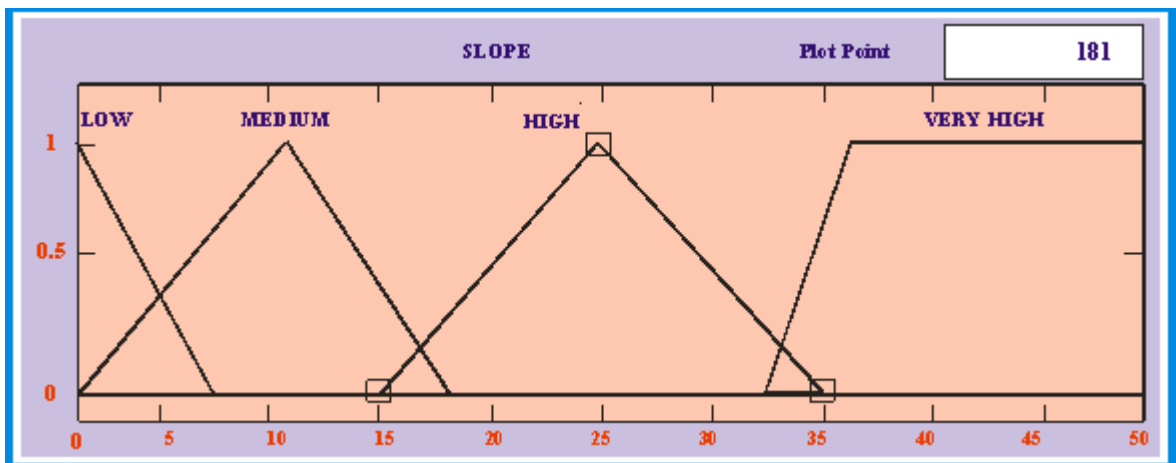


Figure 6.1b: Membership Functions of Slope

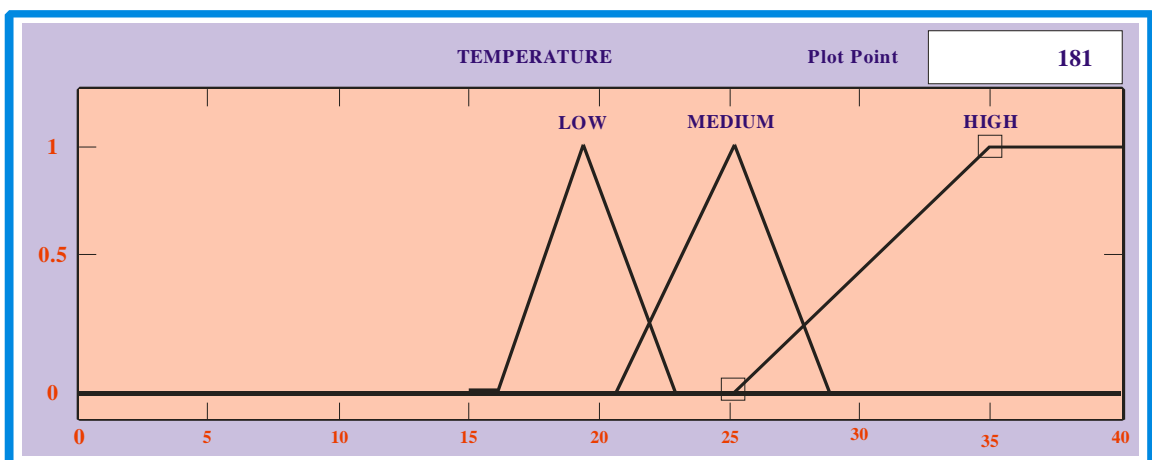


Figure 6.1c: Membership Functions of Temperature

Next, the values of the crop data are mapped onto the membership functions of the three attributes created above. For the sake of displaying the fuzzy logic methodology of approaching degree (described in Section 3.2), it is assumed that the values of the crop criteria can be available in crisp or fuzzy forms.

Case 1: Values of the Crop Criteria are Crisp

Consider the case when the given crop data with respect to the three attributes is available in crisp form.

In this example, assume the crop to be grown is “wheat”. The aim is to identify the most suitable geographical zone among the three PEZ for cultivation of wheat. The criteria of elevation, slope and temperature that describe a given crop are presented as crisp numbers in Table 6.2:

| CROP ↓ | ELEVATION | SLOPE | TEMPERATURE |
|---------------|------------------|--------------|--------------------|
| Wheat | 1500m | 15% | 17.50C |

Table 6.2: Wheat Data (FAO, 2010)

The present method proceeds by checking the suitability of all the three PEZ, for the purpose of cultivating wheat, using data in Table 6.2, membership functions, and the multifeature pattern recognition theory build in Section 3.2.

Consider the analysis of warm lowlands.

The elevation requirements of wheat (1500m) fall outside the range of the linguistic variable LOW that describes the elevation of the warm lowlands. Hence, $\mu(\text{elevation}) = 0$. Similarly, the slope requirements (15%) and the temperature requirements

(17.5°C) of wheat also fall outside the respective ranges of the linguistic variable LOW and HIGH that describe the slope and temperature respectively of the warm lowlands. Hence their membership values are all zeros.

By checking the suitability of the warm cool uplands for the purpose of cultivating wheat, it is found that the elevation requirement of wheat (1500m) falls outside the range of the linguistic variable LOW which describes the elevation of the warm cool uplands. Hence, the corresponding $\mu(\text{elevation}) = 0$. The temperature requirement of wheat (17.5°C) also falls out of the range of the linguistic variable MEDIUM that describes the temperature of the warm cool uplands. So, $\mu(\text{temperature}) = 0$, while the slope requirement of wheat (15%) falls within the range of the linguistic variable MEDIUM that describes the slope of the warm cool uplands. As can be seen from Figure 6.2, $\mu(15\% \text{ slope}) = 0.35$.

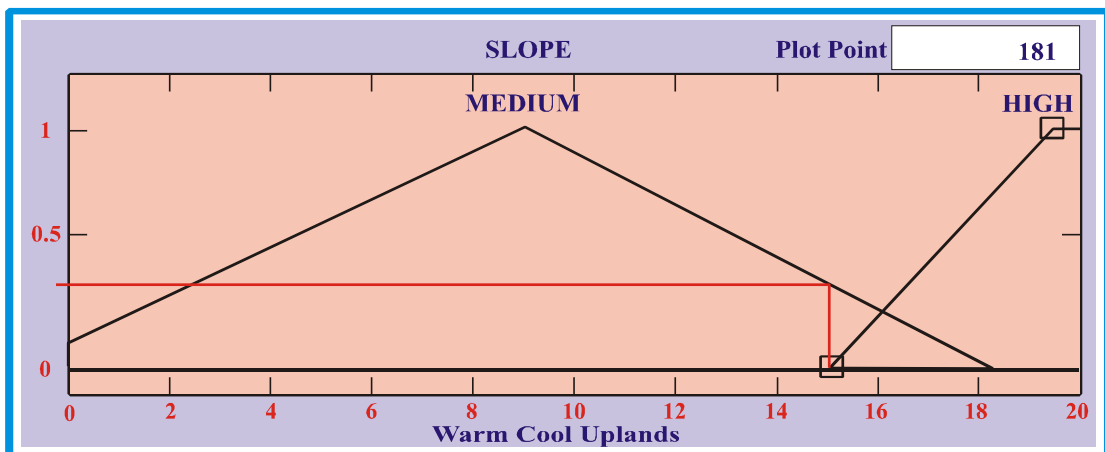


Figure 6.2: Slope Requirements of Wheat Corresponding to the Linguistic Variable MEDIUM of Warm Cool Uplands

Consequently, the approaching degree of wheat to warm cool uplands is given by

$$AD(\text{wheat, warm cool uplands}) = w_1 \mu(\text{elevation}) + w_2 \mu(\text{slope}) + w_3 \mu(\text{temperature}).$$

$$= \frac{1}{3}(0 + 0.35 + 0) = 0.1166. \quad (6.1)$$

Again, for the suitability of the third PEZ cool highlands for cultivation of wheat, the elevation requirement of wheat (1500m) falls within the range of the linguistic variable HIGH that describes the cool highlands. In this case, $\mu(\text{elevation}) = 1$, as can be seen in Figure 6.3.

The triangular fuzzy membership function of elevation is as illustrated in Figures 6.1(a).

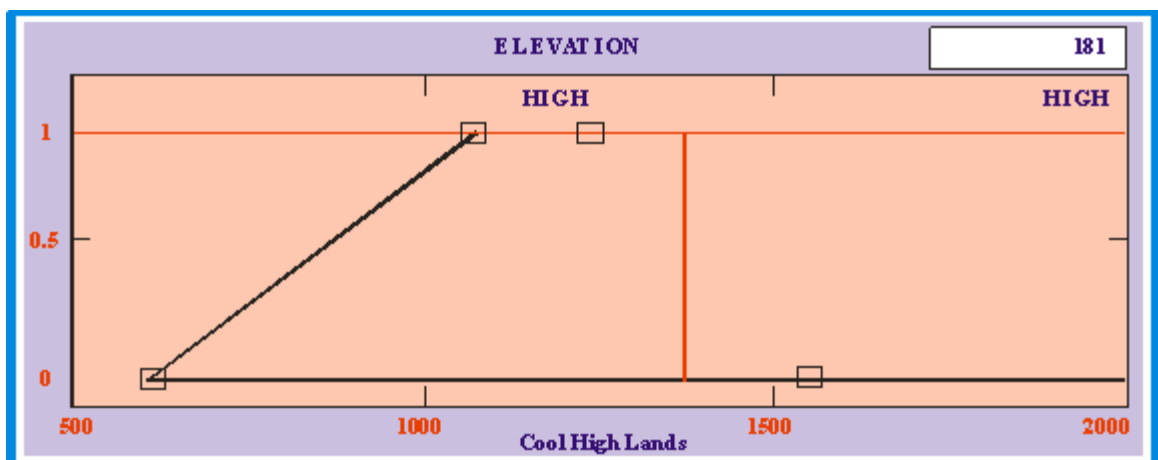


Figure 6.3: Elevation Requirements of Wheat Corresponding to the Linguistic Variable HIGH of Cool Highlands.

The slope requirement falls outside the range of VERY HIGH, and so $\mu(\text{slope}) = 0$, while the temperature falls within the range of variable LOW, and as can be seen from Figure 6.4, $\mu(\text{temperature}) = 0.49$.

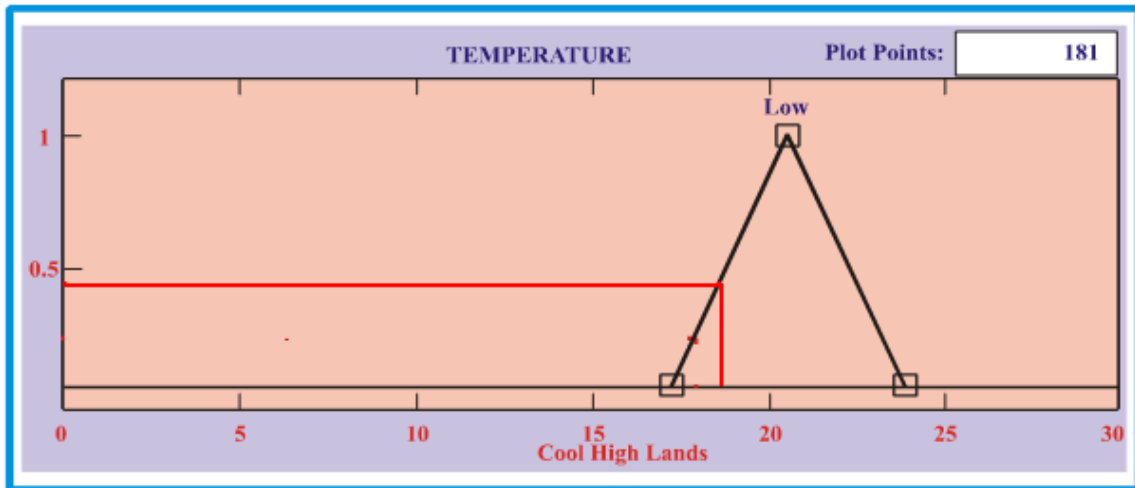


Figure 6.4: Temperature Requirements of Wheat Corresponding to the Linguistic Variable LOW of Cool Highlands.

Using the approaching degree concept, it is clear that the $AD(\text{wheat, cool highlands}) = 1.49/3$ (i.e. 0.4966). The maximum matching degree corresponds to the option of cool highlands and hence it is recommended for cultivation of wheat.

Case 2: Values of the Crop Criteria are Fuzzy

Next consider a case where the criteria of elevation, slope and temperature describing the requirements of a given crop are presented as fuzzy numbers, within ranges of values. For instance, in the case of corn, the data is as follows.

| CROP ↓ | ELEVATION | SLOPE | TEMPERATURE |
|---------------|------------------|--------------|-------------------------------------|
| Corn | 1300-1600m | 0-9% | 8 ⁰ C- 34 ⁰ C |

Table 6.3: Corn Data

Here the elevation and slope data has been obtained from PEZ and the temperature data has been obtained from Corn Data of FAO (2010).

On checking the suitability of warm lowlands for the purpose of growing corn it was found that the elevation requirement of corn (1300-1600m) falls outside the range of the linguistic variable LOW which describes the elevation of the warm lowlands. The same is shown in Figure 6.5, and thus $\mu(\text{elevation}) = 0$.

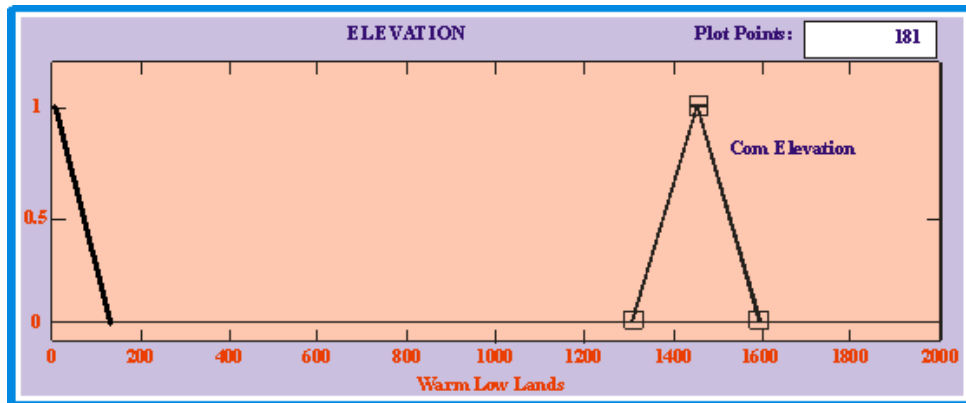


Figure 6.5: Elevation Requirements of Corn Corresponding to the Linguistic Variable LOW of Warm Lowlands

On the other hand, the slope requirement (0-9%) falls within the range of variable LOW, shown in figure 6.6, that describes the slope of the warm lowlands (upper slant line segment) and slope membership function of the corn data (lower slant line segment) superimposed on same graph. Therefore,

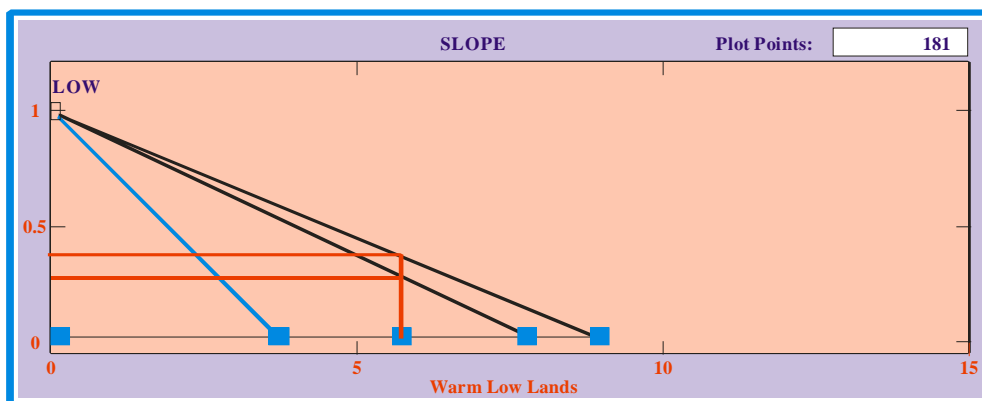


Figure 6.6: Slope Requirements of Corn Corresponding to the Linguistic Variable LOW of Warm Lowlands

$$Low \sqcap x = \max \{ \min [1\wedge 1), (0.65\wedge 0.7), (0.3\wedge 0.35), (0.2\wedge 0), (0\wedge 0)] \} \quad (6.2)$$

$$= 1$$

$$Low \oplus x = \max \{ \min [1\vee 1), (0.65\vee 0.7), (0.3\vee 0.35), (0.2\vee 0), (0\vee 0)] \} \quad (6.3)$$

$$= 0$$

The temperature requirement (8°C - 34°C) falls within the range of the variable HIGH that describes the temperature of the warm lowlands, demonstrated in figure 6.7. The figure 6.7 is the superimposition of two membership functions characterizing the temperature of corn (left graph) and linguistic variable LOW for the warm lowlands.

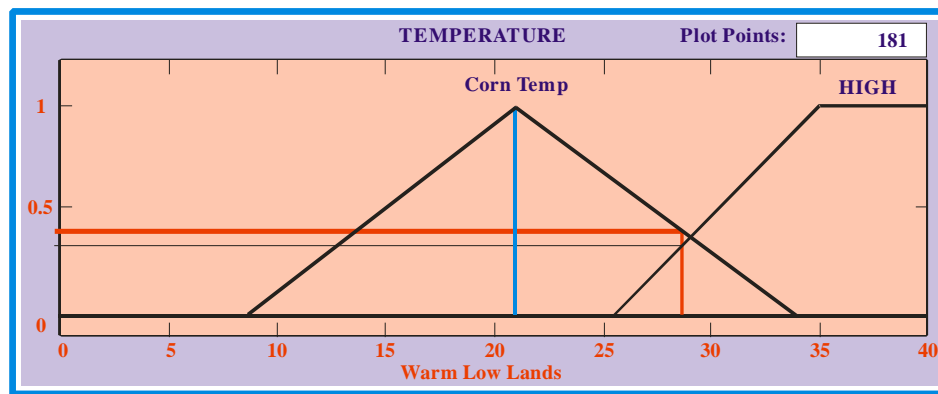


Figure 6.7: Temperature Requirements of Corn Corresponding to the Linguistic Variable LOW of Warm Lowlands

$$High \sqcap x = \max \{ \min [0\wedge 0), (0.52\wedge 0), (1\wedge 0), (0.42\wedge 0.45), (0.44\wedge 0.44), (0\wedge 1)] \} \quad (6.4)$$

$$= 0.44$$

$$High \oplus x = \min \{ \max [0\vee 0), (0.52\vee 0), (1\vee 0), (0.42\vee 0.45), (0.44\vee 0.44), (0\vee 1)] \} \quad (6.5)$$

$$= 0$$

Now calculating the approaching degree value of warm lowlands for corn:

$$AD = \frac{1}{3} \left[\frac{(Low \bullet x) + (Low \oplus x)}{2} + \frac{(Medium \bullet x) + (Medium \oplus x)}{2} + \frac{(High \bullet x) + (High \oplus x)}{2} \right] \quad (6.6)$$

$$AD = \frac{1}{3} \left[\frac{1+0}{2} + 0 + \frac{0.44+0}{2} \right]$$

$$= 0.24$$

Similarly, checking the suitability of the warm cool uplands for cultivating corn, we find, $\mu(\text{elevation}) = 0$, $\mu(\text{slope}) = 0$, and $\mu(\text{temperature}) = 0$. Thus, the approaching degree value is zero. In the case of cool highlands also, the approaching degree of corn turns out to be zero as $\mu = 0$ for all three linguistic criteria, elevation, slope, and temperature. It may be observed from the analysis that warm lowlands are best suited for cultivation of corn.

6.3. Discussion and Conclusions

The decision making process related to sustainability is a subjective issue (Musters, 1998). As a means of supporting this subjectivity, fuzzy set theory enables the linking of human perceptions (expressed in linguistic variables) with numerical data. In this study, we have demonstrated and implemented the concept of approaching degree described using a **fuzzy logic multifeature pattern recognition** tool. The strength of the approach tested herein lies in integrating fuzzy logic in the important decision making process for identifying appropriate land for cultivation of crops. The approach is very flexible in the sense that it can be applied to the situations where the exact data is not available and information on land and crops is limited to the vague subjective descriptions. Although, the approach is illustrated through simple example for the sake of describing the working mechanism, but it can easily be extended to large case scenarios involving many criteria, features, and crops.

However, in spite of these benefits, fuzzy set theory does not allow for explicit inclusion of stakeholder viewpoints, preferences and judgments within the decision making process. Given that the issue of biofuel sustainability has multiple stakeholders (from farmers to policy-makers in government); the inclusion of their viewpoints is indispensable to sustainability related policy design. Hence, in order to allow for the explicit inclusion of stakeholders preferences along with the numerical data, it is proposed to use the Analytical Hierarchy Process, a technique of MCDM. The Chapters to follow will provide a detailed overview of the AHP methodology and the working of the AHP software designed on the basis of the proposed methodology in the case studies. Further, a detailed analysis of the methodologies and the software that made use of the concepts of fuzzy set theory, AHP, Fuzzy AHP, has also been carried out.

Finally it should be noted that the author did not develop software functionality for the fuzzy mathematical model included in this Chapter. The reason is that the Compendium Software lacks a specific fuzzy set support which makes the software capture the readings from the membership functions very difficult. To enable such a capability in software would involve creation of complex fuzzy toolbox/graphics software which is outside the scope of the current research.

Moreover, the present model is deemed deficient because of the following:

- Although fuzzy mathematical model developed has the ability to recommend the most suitable option, it is unable to recommend options and policies for the long term future which is indispensable as far as policy design is considered.

- In the present model, the subjectivity of expert with linguistic expressions makes it very difficult to achieve a single consensus or group consistency (Iyer and Sagheer, 2007). This means the same linguistic variable may be interpreted in vastly different manners by different stakeholders in the group, thereby rendering ineffective as far as Group Decision Support (GDS) goes. GDS is an interactive, computer based system that facilitates the solution of problems by a set of decision makers working together as a group (DeSanctis and Gallupe, 1987).

On the contrary, AHP is well suited to group decision-making as it provides a logical means of synthesizing judgments which are easily tracked through computations and may be revised as the situation warrants (Dyer and Foreman, 1992).

Keeping in the mind the shortcomings of the fuzzy logic multifeature pattern recognition model that has been developed, it has been decided to overcome these by incorporating an AHP Matrix whose details are discussed in Chapter 7. This redefinition has offered a much more detailed investigation of sustainable biofuel production, integrating those variables and policies which can improve biofuel sustainability in long term.

CHAPTER 7: THE AHP CASE STUDY FOR BIOFUEL CROP CULTIVATION

This Chapter includes a case study carried out for selection of a suitable option from various biofuel crops such as sugarcane, maize, jatropha. This case study illustrates how AHP can fruitfully be used to determine the optimum biofuel crop from an agro-environmental and technical perspective. Selection of a suitable agricultural crop for biofuel production is necessary in order to address the sustainability concerns surrounding biofuel production.

7.1 Criteria and Options Priority Weights

The AHP methodology is applied to the study of agricultural crops that may be used for biofuel production. Therefore in the present methodology, the selection of the crop is based broadly on three criteria- Environmental, Agricultural and Technological¹⁵. These criteria in turn are divided into a number of sub-criteria. The data related to the chosen criteria and their sub-criteria for different biofuels crops is shown in Figure 7.1, where P (High) and P (Low) represent the highest and lowest possible values for a particular criterion in the geographical region. The case study in the present Chapter is carried out for India (data taken from Appendix 2).

¹⁵ From a survey of literature on biofuel sustainability it appears that important reasons for selecting one crop over another can be described in terms of criteria that are environmental, agricultural and technological in nature (RSPO, 2008). Some of the environmental and agricultural aspects of biofuel sustainability have already been discussed in detail in Chapter 2.

| Sub-Criteria | SWEET SORGHUM | SOYBEAN | SUNFLOWER | RAPESEED | JATROPHA | MAIZE | SUGARCANE | P(High) | P(Low) |
|-------------------------|---------------|---------|-----------|----------|----------|--------|-----------|---------|--------|
| Land_Under_Cultivation | 29.035 | 7.64 | 2.25 | 7.3 | 0.425 | 7.51 | 3.93 | 20.04 | 0.4 |
| Yield/hectare | 1162.5 | 990.5 | 582 | 1077.5 | 3750 | 1922.5 | 65040 | 66928 | 549 |
| Precipitation_tolerance | 11.7 | 22.05 | 21 | 15.5 | 6.5 | 21.65 | 23.8 | 42.9 | 2 |
| soil_ph | 6.55 | 6.35 | 6.6 | 4.5 | 6 | 6.5 | 6.35 | 8.7 | 4.2 |
| Water_Requirement | 575 | 600 | 550 | 160 | 650 | 650 | 975 | 1200 | 80 |
| Cotone_Number | 8.5 | 53 | 52 | 56.5 | 58 | 53 | 8.5 | 70 | 8 |
| Iodine_Number | 0 | 77.5 | 130 | 106 | 97.5 | 119.5 | 0 | 135 | 60 |
| Cloud_Point | -15 | -13.5 | -13.5 | -13.5 | -13.5 | -15 | -15 | 22 | -11 |
| Flesh_Point | 13 | 122 | 122 | 122 | 122 | 13 | 13 | 122 | 13 |
| Pour_Point | -117.3 | 9 | 9 | 9 | 9 | -117.3 | -117.3 | 9 | -117.3 |
| Heat_of_Combustion | 27 | 39.6 | 39.6 | 39.6 | 39.6 | 27 | 27 | 39.6 | 27 |
| Oil_Content | 30 | 20 | 44 | 37.5 | 51 | 75 | 80 | 80 | 25 |
| Oil_Yield | 6000 | 446 | 952 | 1190 | 1892 | 172 | 5052 | 6000 | 172 |
| Total_Energy_Used | 42.5 | 31.9 | 59.7 | 41.7 | 49.9 | 0 | 139 | 139 | 31.9 |
| Water_Footprint | 419 | 177 | 0 | 165 | 574 | 110 | 108 | 574 | 108 |
| Energy_balance | 0 | 3 | 3.2 | 2.7 | 0 | 1.5 | 8.3 | 8.3 | 1.5 |
| GHG_Emissions | 0 | 2.39 | 0 | 2.89 | 0 | 1.13 | 1.7 | 2.89 | 1.13 |

Figure 7.1: Actual Data of Crops

The AHP analysis is performed on a four level hierarchy (Chapter 3). The first level of hierarchy comprises the goal, which in the present case is to select an appropriate biofuel crop for a Indian region. The second level consists of the 3 criteria: environmental, agricultural and technological. The sub-criteria constitute the third level of hierarchy. The final fourth level has 7 biofuel crops options from which to choose from. The 7 biofuels considered are sweet sorghum, soybean, sunflower, rapeseed, jatropha curcas, maize, and sugarcane.

First, the pairwise comparisons of the three criteria are created by listing the preference for one criterion over another on the scale of 1-9 (explained in Chapter 3). A 3x3 matrix depicted in Figure 7.2 is formed. As this is purely an illustrative example, weightings have been chosen by the author. It is important to mention here that the entries in Figure 7.2 are determined by the user according to his or her preference. For instance, the value of $a_{12} = 0.304$ implies that according to the stakeholder perception, the agricultural criteria is only 0.304 times the relevance of the environmental criterion. Moreover, for this matrix, the consistency ratio (CR) =

0.013 < 0.1 (value taken from Figure 7.5), showing that this matrix is acceptably consistent, and hence the analysis can proceed further.

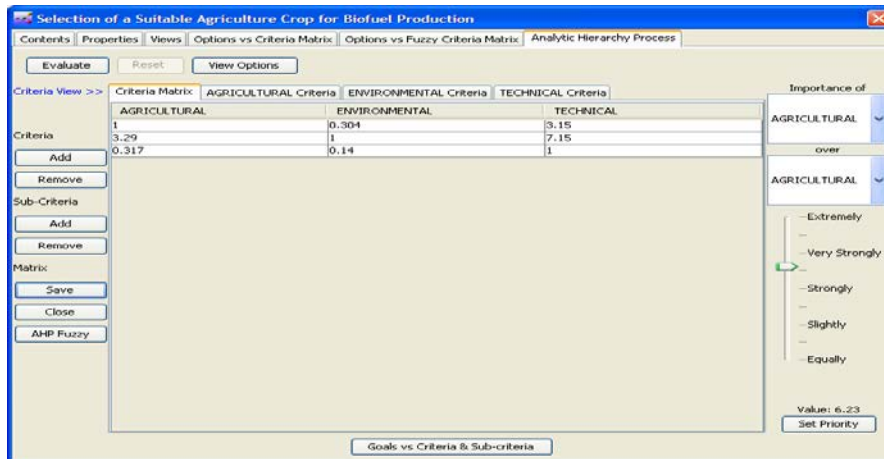


Figure 7.2: A Pairwise Comparison Matrix of Criteria

Next, the sub-criteria relevant to each of the criteria that have been identified and incorporated within the decision matrix. Figure 7.3, indicates that the agricultural criterion has been decomposed into five constituent sub-criteria which are land under cultivation, yield/hectare, precipitation tolerance, soil pH, and water requirements. Subsequently, pairwise comparisons that indicate the importance of one sub-criterion over another are entered.

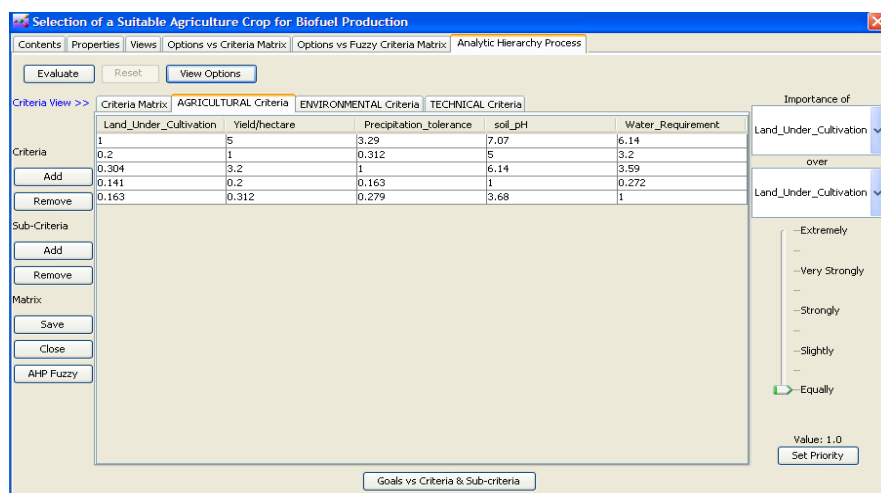


Figure 7.3: Pairwise Comparison Matrix of Sub-Criteria with respect to Agricultural Criterion

The same procedure is adopted to compare the remaining sub-criteria with respect to each of their preceding criteria, environmental criteria and technical criteria on the 1-9 Saaty scale. The other two sub-criteria matrices obtained are found to be consistent with $CR = 0.01914$ and 0.03721 respectively (which are < 0.1).

Similarly we proceed to enter the pairwise comparisons pertaining to each of the options. This is owing to the fact that stakeholder preferences for the options may vary for each individual criterion (Saaty, 2005).

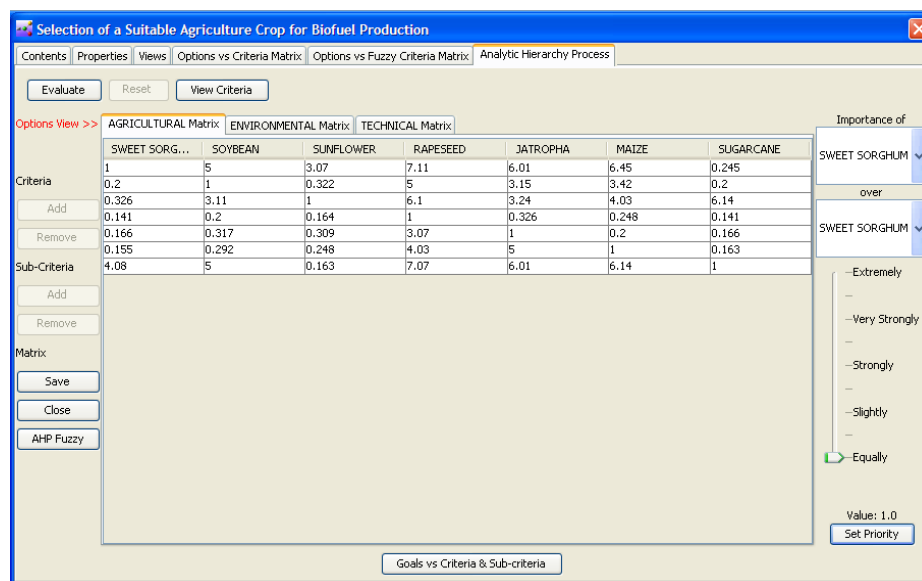


Figure 7.4: A Pairwise Comparison Matrix of Options with respect to Agricultural Criterion

Using the maximum Eigenvalue and eigenvector method of Saaty (1980), as explained in Chapter 3, the local priority weights of the criteria (w_c), sub-criteria (w_{sc}) and that of the options (w_o) are calculated. These other weights are subsequently used to obtain the composite weights/ absolute weights. The values of these priority weights are obtained from Figure 7.4 and tabulated in Table 7.1 for the agricultural criterion (where calculation of global weights is shown).

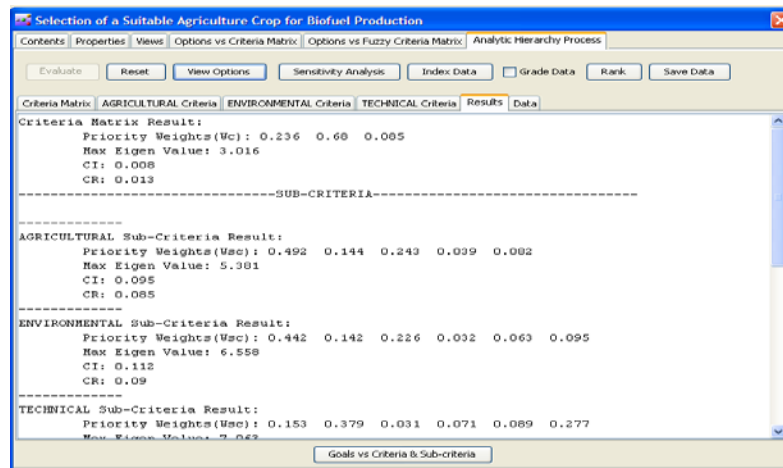


Figure 7.5: Priority weights of Criteria

| Criteria | Priority Weight of Criteria (w _c) | Priority Weight of Sub-Criteria (w _{sc}) | Global/Absolute Weight of Sub-Criteria | Priority Weight of Options (w _o) | Global Weights (w _g) |
|-------------|---|--|--|--|--|
| Agriculture | 0.236 | 0.492 | 0.236*0.492=0.116 | 0.267 | w _g of option1 (sweet sorghum): |
| | | 0.144 | 0.236*0.144=0.034 | 0.089 | 0.267*0.116 |
| | | 0.243 | 0.236*0.243=0.057 | 0.245 | 0.267*0.034 |
| | | 0.039 | 0.236*0.039=0.009 | 0.02 | 0.267*0.057 |
| | | 0.082 | 0.236*0.082=0.019 | 0.039 | 0.267*0.009 |
| | | | | 0.069 | 0.267*0.019 |
| | | | 0.272 | | |

Table 7.1: Calculation of the Absolute Weights

After obtaining the absolute weights for a given set of decision parameters from the AHP, the decision maker can now compare different options available on the basis of quantitative data. However, before doing so, the conditioning of data needs to be done.

7.2. Data Conditioning: Indexing and Grading the Data

The data collected for the purpose of selecting an optimum option from a number of available alternatives may be of different units and orders of magnitude. Hence, there is a need to condition the data into similar units by the use of data conditioning techniques like normalizing or indexing. For the purpose of the present research, indexing of data has been carried out as it allows the data to be expressed in the form of dimensionless ratio. This is achieved by dividing the numerical data by a single performance value with the same units. For the purpose of indexing the actual data (Figure 7.1), the element in the first cell of each row is regarded as the base and the rest of the elements in that row are divided by it to generate the ratio scales (Chee Tahir, 2006). An optional provision for grading of indexed data is provided which allows users to scale and order the indexed quantitative data so it falls within the range of a specifically chosen scale. The quantitative data may be graded using the linear interpolation equation (Chee Tahir, 2006):

$$S = \frac{P_{data} - P_{low}}{P_{high} - P_{low}} * 100, \quad (7.1)$$

where P_{data} is the numerical data of the given criteria and P_{high} and P_{low} are the limiting values corresponding to respectively the best and the worst case for the given criterion in the given area of study.

| Criteria Matrix | AGRICULTURAL Criteria | ENVIRONMENTAL Criteria | TECHNICAL Criteria | Results | Data | Indexed Data | Graded Data | Final Ranking | |
|-------------------------|-----------------------|------------------------|---------------------|---------|------|--------------------|---------------------|---------------------|--------------------|
| Sub Criteria | SWEET SORGHUM | SOYBEAN | SUNFLOWER | | | RAPESEED | JATROPHA | MAIZE | SUGARCANE |
| Land_Under_Cultivation | 145.79938900203666 | 36.86354378818737 | 9.419551934826883 | | | 35.13238289205703 | 0.12729124236252534 | 36.20162932790224 | 17.973523421588595 |
| Yield/hectare | 0.9242380873469019 | 0.6651199927687974 | 0.04971451814579911 | | | 0.7961855406077224 | 4.822308260142514 | 2.0691785052501546 | 98.3609274017385 |
| Precipitation_tolerance | 23.716381418092904 | 49.02200488997555 | 46.45476772616136 | | | 33.007334963325185 | 11.00244498777506 | 48.0440097799511 | 53.30073349633252 |
| soil_pH | 52.22222222222222 | 47.77777777777777 | 53.33333333333314 | | | 6.666666666666662 | 39.99999999999999 | 51.11111111111111 | 47.77777777777777 |
| Water_Requirement | 44.19642857142858 | 46.42857142857143 | 41.964285714285715 | | | 7.142857142857143 | 50.892857142857146 | 50.892857142857146 | 79.91071428571429 |
| Cetane_Number | 0.8064516129032261 | 72.58064516129033 | 70.96774193548387 | | | 78.22580645161293 | 80.64516129032258 | 72.58064516129033 | 0.8064516129032261 |
| Iodine_Number | 100.0 | 100.0 | 100.0 | | | 100.0 | 100.0 | 100.0 | 100.0 |
| Cloud_Point | 100.0 | 100.0 | 100.0 | | | 100.0 | 100.0 | 100.0 | 100.0 |
| Flash_Point | 0.0 | 100.0 | 100.0 | | | 100.0 | 100.0 | 0.0 | 0.0 |
| Pour_Point | 100.0 | 100.0 | 100.0 | | | 100.0 | 100.0 | 100.0 | 100.0 |
| Heat_of_Combustion | 0.0 | 100.0 | 100.0 | | | 100.0 | 100.0 | 0.0 | 0.0 |
| Oil_Content | 9.090909090909092 | -9.090909090909097 | 34.54545454545455 | | | 22.72727272727273 | 47.27272727272727 | 90.90909090909092 | 100.0 |
| Oil_Yield | 100.0 | 4.701441317776252 | 13.38366506520247 | | | 17.46739876458476 | 29.512697323266988 | 0.0 | 83.73369938229237 |
| Total_Energy_Used | 9.897292250233425 | 0.0 | 25.957049486461255 | | | 9.15032679738562 | 16.806722689075627 | -29.785247432306257 | 100.0 |
| Water_Footprint | 66.7381974248927 | 14.806866952789699 | -23.175965665236056 | | | 12.23175965665236 | 100.0 | 0.4291845493562221 | 0.0 |
| Energy_balance | 100.0 | 100.0 | 100.0 | | | 100.0 | 100.0 | 100.0 | 100.0 |
| GHG_Emissions | 100.0 | 100.0 | 100.0 | | | 100.0 | 100.0 | 100.0 | 100.0 |

Figure 7.6: Graded Data

The graded data seen in Figure 7.6 and the global weights W^a obtained from Table 7.1 are used to derive the final ranking of the 7 options by using the expression:

$$Total\ Marks_{oi} = \sum_{j=1}^{16} S_{ij} * W^a_{ij}, \quad i = 1, \dots, 7. \quad (7.2)$$

Here, $Total\ Marks_{oi}$ denotes the total marks obtained by the i -th option. The options are then ranked in descending order of their total marks.

7.3. Final Ranking

With the data and absolute weights of the criteria associated with various decision options known, the total marks of the various options are calculated and the results listed in Figure 7.7.

| Sub-Criteria | SWEET SORGHUM | SOYBEAN | SUNFLOWER | RAPESEED | JATROPHA | MAIZE | SUGARCANE |
|-------------------------|---------------|---------|-----------|----------|----------|--------|-----------|
| Land_Under_Cultivation | 1.4879 | 0.6108 | 0.1564 | 0.5822 | 0.0021 | 0.5999 | 1.6538 |
| Yield/hectare | 0.4844 | 0.4844 | 0.4844 | 0.4844 | 0.4844 | 0.4844 | 0.4844 |
| Precipitation_tolerance | 0.1942 | 0.4013 | 0.3803 | 0.2702 | 0.0901 | 0.3933 | 0.4364 |
| soil_pH | 0.0681 | 0.0623 | 0.0695 | 0.0087 | 0.0522 | 0.0667 | 0.0623 |
| Water_Requirement | 0.1216 | 0.1277 | 0.1154 | 0.0197 | 0.14 | 0.14 | 0.2198 |
| Cetane_Number | 3.8524 | 1.5815 | 0.405 | 1.5074 | 0.0055 | 1.5531 | 4.2819 |
| Iodine_Number | 1.3832 | 1.3832 | 1.3832 | 1.3832 | 1.3832 | 1.3832 | 1.3832 |
| Cloud_Point | 0.5198 | 1.0744 | 1.0182 | 0.7235 | 0.2412 | 1.053 | 1.1682 |
| Flash_Point | 0.1638 | 0.1499 | 0.1673 | 0.0209 | 0.1254 | 0.1603 | 0.1499 |
| Pour_Point | 0.2701 | 0.2838 | 0.2565 | 0.0437 | 0.311 | 0.311 | 0.4884 |
| Heat_of_Combustion | 0.0074 | 0.6669 | 0.6521 | 0.7188 | 0.741 | 0.6669 | 0.8448 |
| Oil_Content | 0.1661 | 0.0682 | 0.0175 | 0.065 | 2.0E-4 | 0.067 | 0.1846 |
| Oil_Yield | 0.4587 | 0.4587 | 0.4587 | 0.4587 | 0.4587 | 0.4587 | 0.4587 |
| Total_Energy_Used | 0.0090 | 0.0187 | 0.0177 | 0.0126 | 0.0042 | 0.0183 | 0.0203 |
| Water_Footprint | 0.0449 | 0.0411 | 0.0459 | 0.0057 | 0.0344 | 0.044 | 0.0411 |
| Energy_balance | 0.0478 | 0.0502 | 0.0454 | 0.0077 | 0.055 | 0.055 | 0.0864 |
| GHG_Emissions | 0.0027 | 0.243 | 0.2376 | 0.2619 | 0.27 | 0.243 | 0.3078 |
| Marks/TOTAL | 9.2821 | 7.7061 | 5.9111 | 6.5743 | 4.3986 | 7.6978 | 12.272 |
| Rank | 2 | 3 | 6 | 5 | 7 | 4 | 1 |

Figure 7.7: Final Ranked Matrix

The above analysis shows that the crop alternatives of **sugarcane** followed by **sweet sorghum** are best suited for biofuel production.

The result is not surprising. In fact sugarcane based bio-ethanol is overall favourite with biofuel producers. So much so that it formed the backbone of Brazil's successful Pro-Alcohol program launched in 1975 that aimed at phasing out fossil fuels like gasoline (used in automobiles) in favour of ethanol produced from sugarcane. According to Sperling and Gordon (2009), sugarcane based ethanol is the most successful alternative fuel to date.

However, in spite of the performance benefits offered by sugarcane, according to Sperling and Gordon (2009) the Brazilian ethanol model is sustainable only in Brazil, given its abundance of agricultural resources. Policy-makers and stakeholders in other countries may have to explore other crop options for sustainable biofuel production suited to their existing resource bases. The stakeholders or policy-makers may have to

consider other scenarios to achieve a desired biofuel production outcome. The scenario planning technique provides a rational way of considering the future, not through the guesswork of predictions, but through testing the consequences of the actions and decisions of policy makers in context of different and distinct possible future scenarios (Darton, 2003). The use of the AHP to aid scenario planning will be discussed in the next Chapter.

CHAPTER 8: SCENARIO PLANNING FOR SUSTAINABILITY POLICY DESIGN

Besides determining the priorities of alternatives in MCDM problems, the AHP methodology has also been successfully used to inform policy design and management. Policy design is a dynamic and purposeful activity intended to steer a system from a likely outcome to a desired future outcome (Saaty, 1980). In assisting the designing and choosing policies, AHP can be useful in providing a technique for comparing options. In context of AHP, policy planning has been studied in literature in the following two aspects:

- **Projected Future:** Represents the future scenario when current policies remain unchanged and carry on into the future.
- **Desired Future:** What policies are needed to achieve a desired future scenario?

AHP has been involved in planning and policy designing in many fields, namely, energy planning (Loken, 2007), natural resource management (Schmoldt et al. 2007), alternative waste treatment policies (Saaty, 1982), water resource policies (Mei et al. 1989), to name a few. These studies indicate that multi-criteria decision making tools, like AHP, provide better understanding of inherent features of decision problem, promote the role of participants in decision making process, facilitate compromise and collective decisions and provide a good platform for understanding the perception of models' and analysts' in a realistic scenario (Pohekar and Ramachandran, 2004).

Previous Chapters have examined the importance and need of biofuels development as an alternative and renewable source of energy. The development of this sector demands both short and long range well coordinated planning, vision and execution at all levels. Adopting an inappropriate program may have negative impact on

sustainability which have not been foreseen. There are many factors, including geographical and economic, which influence the policy making or mission for achieving a gradual increase in biofuels capacity of the region. The purpose of this Chapter is to identify the direction of solutions and attempt to answer a question: *What policy improvement options can be proposed to stimulate wide-scale adoption of the “identified biofuels crop” to be grown at large scale in the region.*

The present Chapter seeks for “the policies” that will gradually enhance the production of a given crop by some year X_{future} in future.

In the sections to follow, an AHP analysis is performed to evaluate four possible policies that can be implemented to enhance the desired crop production in future. This is achieved through an iterative forward-backward AHP forecasting process (Saaty, 1980) which evaluates the set of necessary policies. The Chapter thus demonstrates how the AHP functionality developed as a part of this research can be used for supporting biofuel policy formulation.

8.1. Forward-Backward Forecasting

Our first target is to analyze and identify the most suitable biofuel crop to be grown in the Indian regions with success. This is achieved through the four levels AHP analysis, which shall be called the first forward process. In fact to assess the potential future scenarios rather than the existing biofuel crops production schemes, Poh and Ang (1999) advocated the use of a forward-backward planning mechanism. Using the AHP, the likely future is projected through forward planning to assess future priorities. The necessary steps or policies to achieve this intended future are found through backward planning or backcasting. Consequently, the forward- backward

planning mechanism can be thought of as a feedback controller which attempts to gradually tune in the overall final scenario as intended by the policy makers by seeking feedback from the actual stakeholders. The details of the procedure are outlined below.

First Forward Process

In Chapter 7, **sugarcane** had been obtained as the optimum biofuels crop option taking into account environmental, agricultural and technical considerations. However, if the goal for future biofuel production in the year X_{future} is environmental sustainability (inclusive of agricultural consideration); the present hierarchy needs to be re-evaluated using only the relevant criteria to see what the preferred option would be in future. The desired future is projected through forward planning. The hierarchy developed for this purpose is called the first forward hierarchy. This hierarchy takes into consideration only the environmental and agricultural criteria. The hierarchy continues to enjoy four level structure with two criteria at level 2, their sub-criteria at level 3, followed by biofuels crops options at level 4. Subsequently, the AHP analysis is performed on the same data except we now only have two criteria (and their related subcriteria) as shown in Figure 8.1.

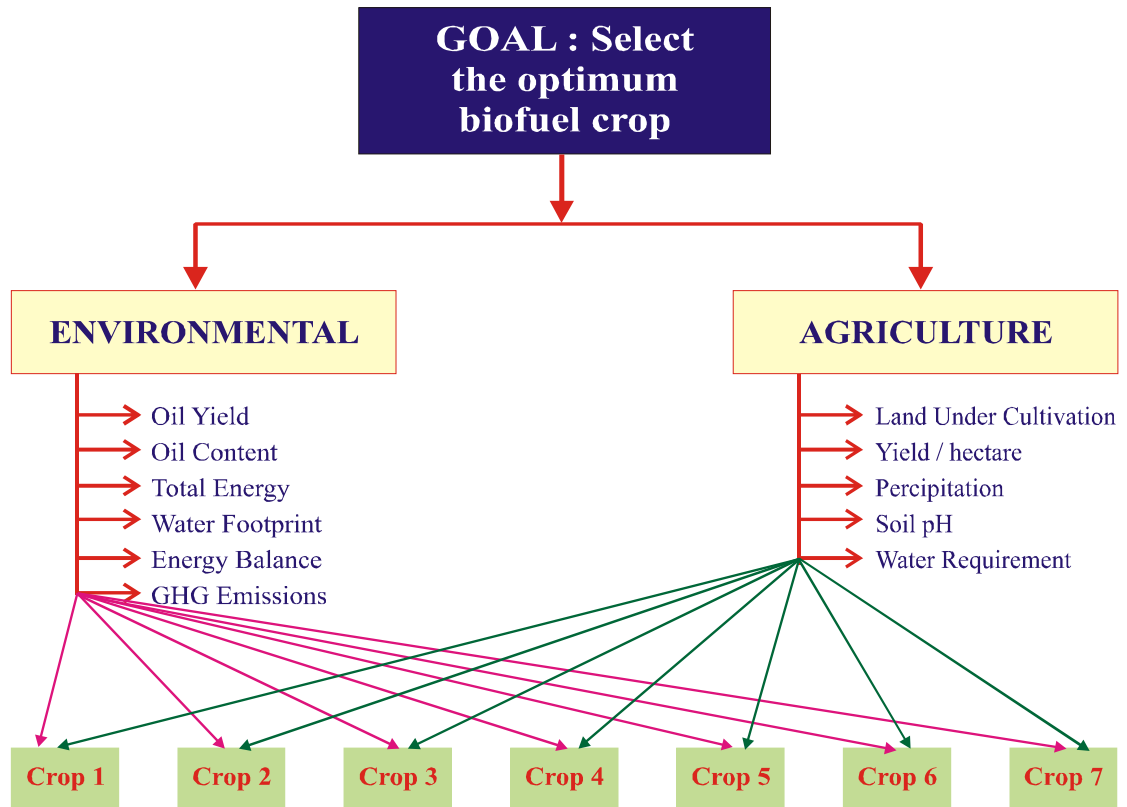


Figure 8.1: Four levels AHP decision hierarchy for first forward process

Figures 8.2, 8.3 and 8.4 respectively show the pairwise comparison of the 2 criteria- environment and agriculture, environment sub-criteria, and the 7 crops options with respect to environment criterion. Similar to the environment sub-criteria, the agriculture sub-criteria comparison matrix and the 7 crops options comparison matrix with respect to agriculture criterion have also been used in the analysis.

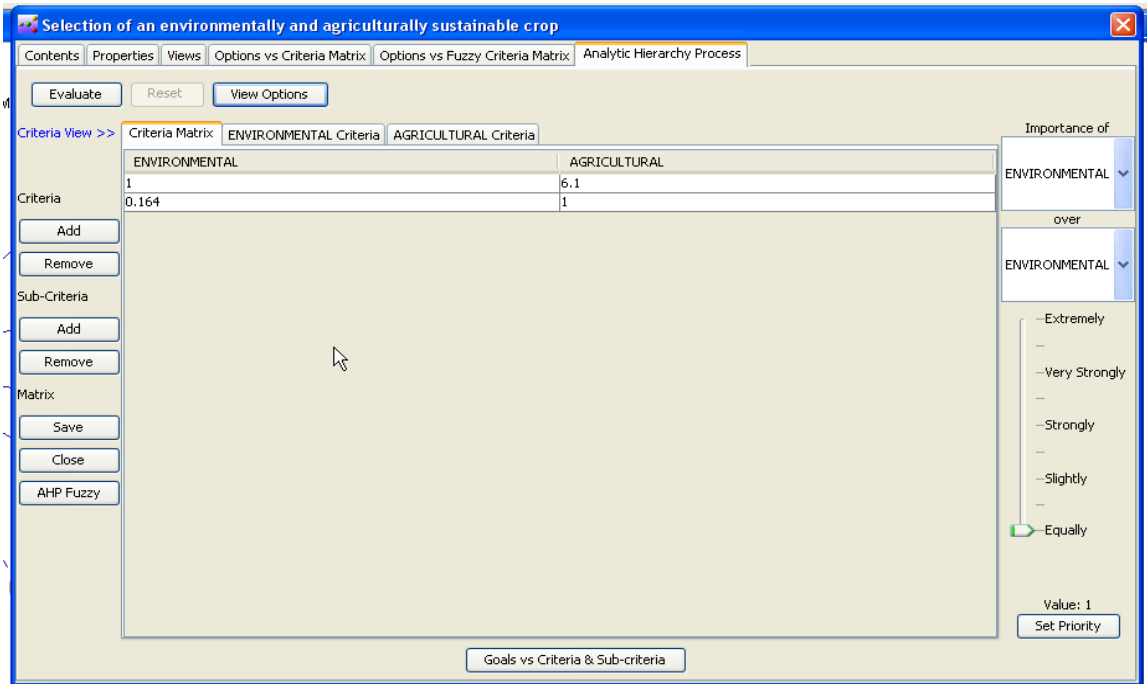


Figure 8.2: Pairwise Criteria Matrix at Level 1

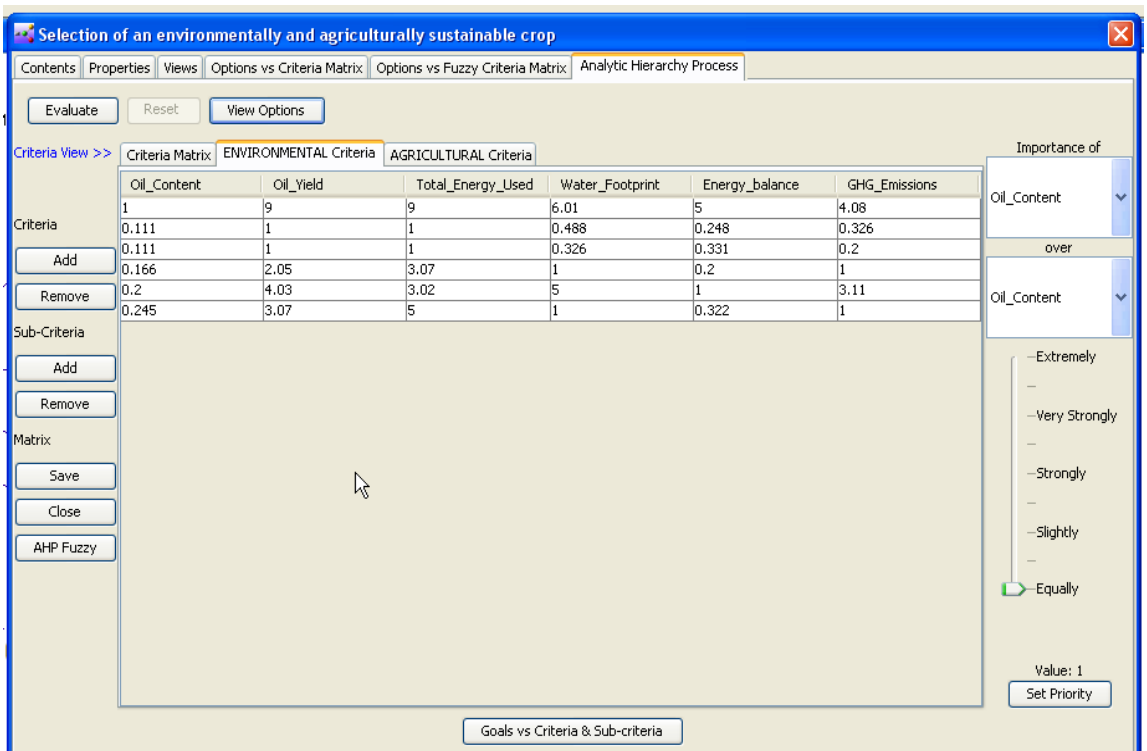


Figure 8.3: Pairwise Sub-Criteria Matrix related to the Environmental Criteria

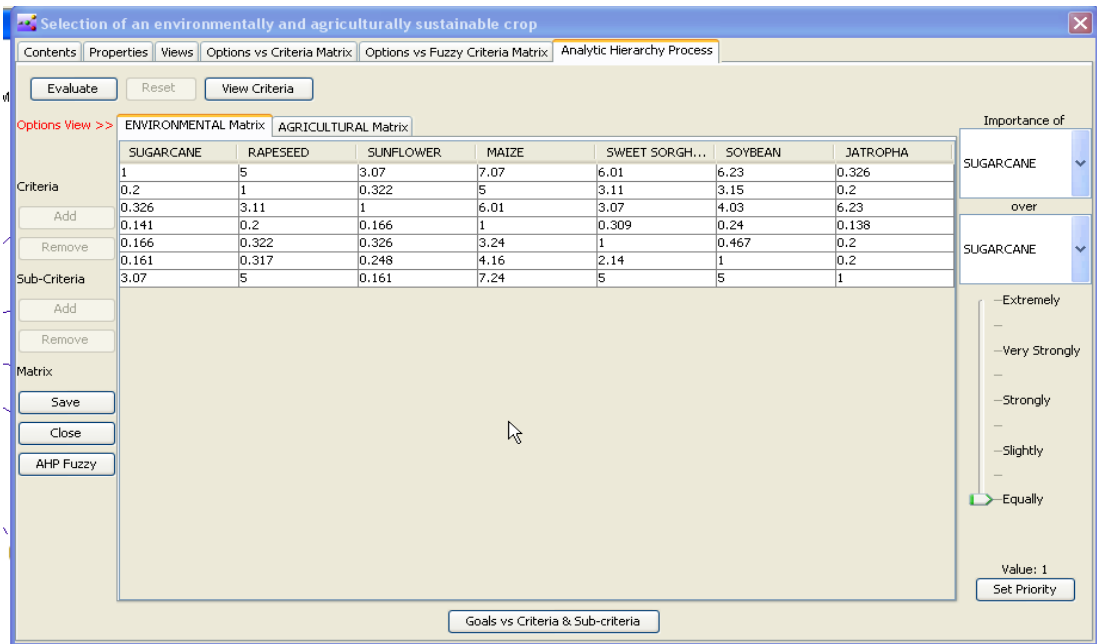


Figure 8.4: Pairwise Comparison of Options

From the data in Figures 8.2, 8.3 and 8.4, the priority weights are computed and the results displayed in Figure 8.5.

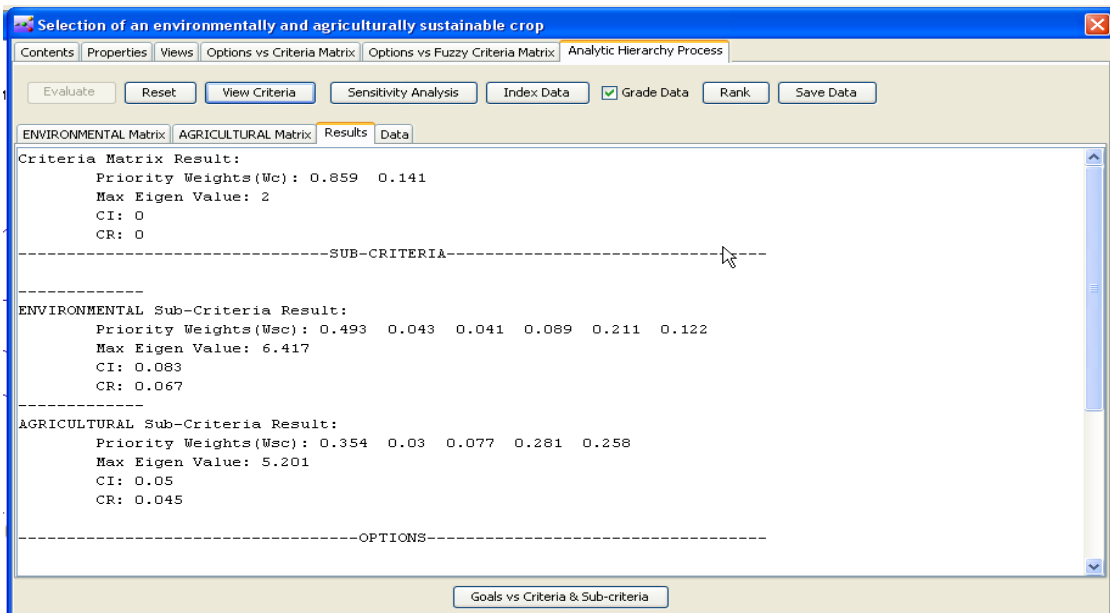


Figure 8.5: Priority weights (W_c and W_0)

Once judgments have been entered for each part of the model, the information is synthesized to achieve the overall preference. The synthesis produces a report which ranks the alternatives in relation to the overall goal. The summary of the ranking of alternatives is given in Figure 8.6.

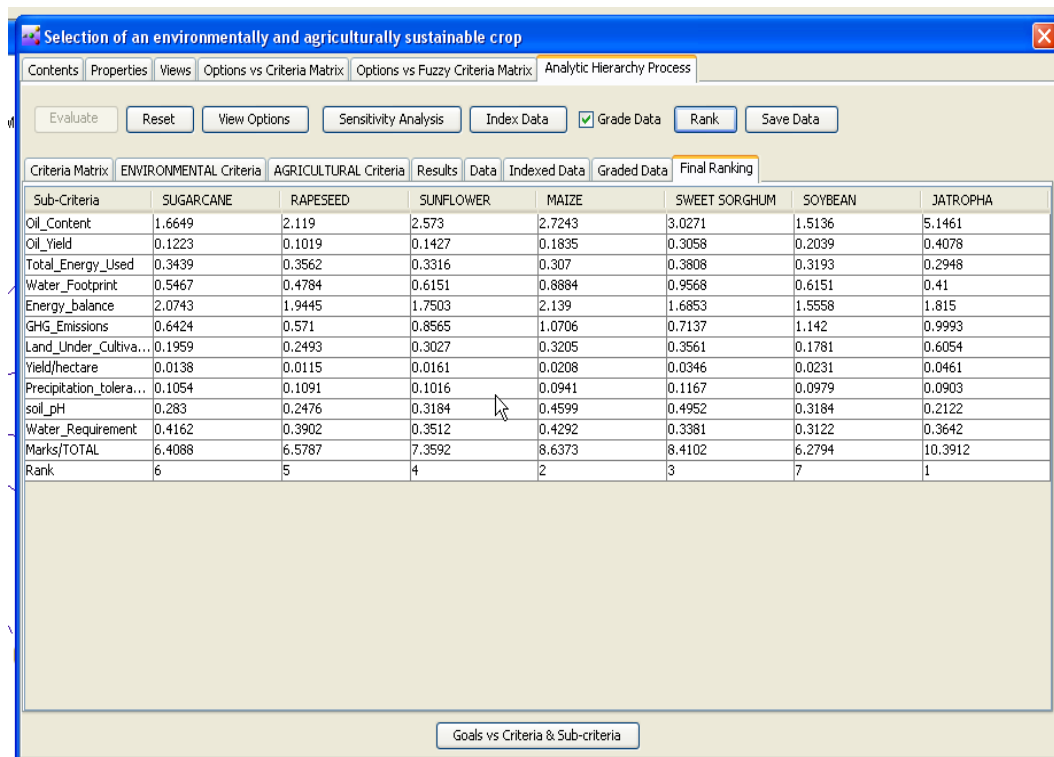


Figure 8.6: Ranking of Crops based on Environmental and Agricultural Criteria

Figure 8.6 that, from an environmental and agricultural view point, the **Jatropha curcas** is an optimum crop (as opposed to sugarcane). This is not very surprising. For mitigating climate change by reducing emission of green house gases, meeting energy needs, protecting the environment and generating gainful employment, Jatropha curcas has multiple roles to play. It is a tropical plant that can be grown in low rainfall areas, including drought prone areas (Openshaw, 2000). Given that it is an easily cultivable crop which requires very low inputs, it is regarded as a suitable energy crop for developing countries like Tanzania (van Eijck and Romijin, 2008), India, and Nicaragua.

First Backward Process

However, given the high value in terms of by-products and utility of sugarcane, the stakeholders obviously may still prefer the status quo and continue to grow more sugarcane for biofuels. To change this scenario and to make them shift from sugarcane to *Jatropha curcas*, policy makers need to design certain policies to encourage growing *Jatropha*. Views from the technology, the local policies and local socio-economic organizations, and agro industries need to be included in designing future policies for the desired results.

The first backward process determines the actions that are necessary (and most effective) to achieve the predicted outcome of the first forward process. In the present case study, for the sake of illustration, we identify the following four possible policies (adapted from Poh and Ang, 1999). These are representative policies to enable producers to meet the expected supply scenario over the predetermined time period X_{future} .

| | |
|-----------------------|---|
| Policy P ₁ | Setting a minimum % biofuel transport fuels. |
| Policy P ₂ | Adoption of stricter emission rules (create a market demand for biofuels) |
| Policy P ₃ | Providing infrastructure to increase the availability and accessibility of biofuels to the consumers |
| Policy P ₄ | Provision of financial incentives to the farmers in the form of farm subsidies and availability of easy credit. |

Table 8.1: Possible Policies which may Help Achieve the Required Future Outcome

The AHP analysis is carried to rank the four policies; now the policies occupy the place of options at the bottom level of the previous hierarchy (Figure 8.1). Since the choice of biofuel options for the future year X_{future} depends on its environmental sustainability (along with agricultural considerations), the optimum ranking of the four policies is obtained taking into account the environmental and agricultural considerations listed in Figure 8.1. The stakeholders' viewpoints and experts' opinion are recorded again in the light of the four proposed policies. Changes in their preference will be reflected through the pairwise comparison of criteria and options. The pairwise comparison of the criteria (displayed in Figure 8.7) is carried out and it illustrates a situation where the preference of one criterion over another has changed.

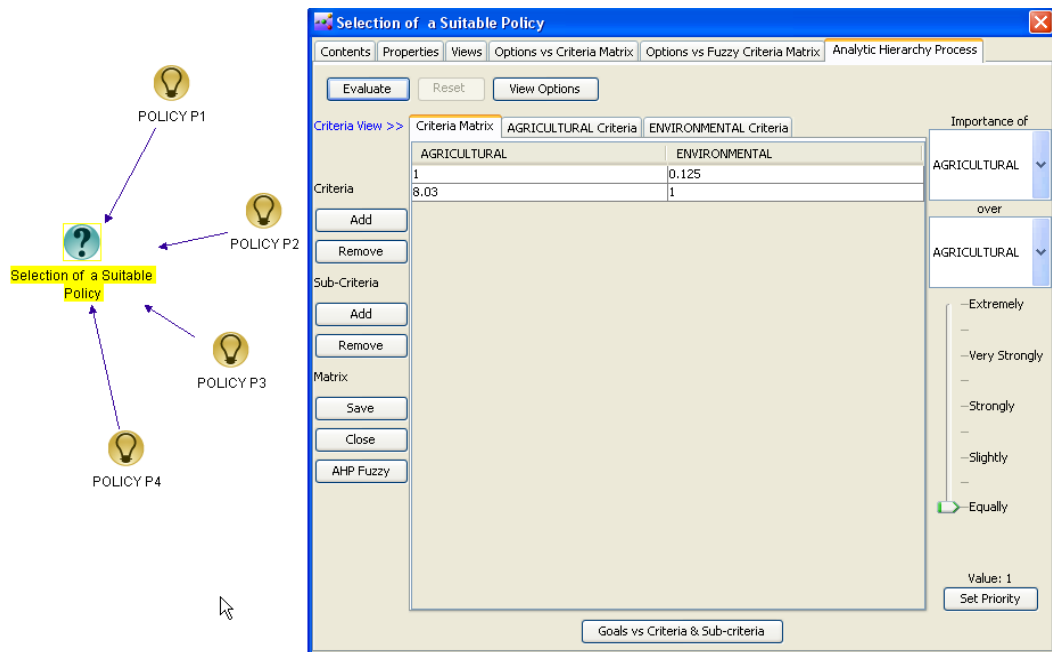


Figure 8.7: Pairwise Criteria Matrix

Subsequently, the pairwise comparison of the policies with respect to a given criterion is carried out. The priority weights of the criteria and policies (options) thus obtained

(shown in Figure 8.8) are used to calculate the absolute weights which in turn provide the final ranking of the policies (shown in Figure 8.9).

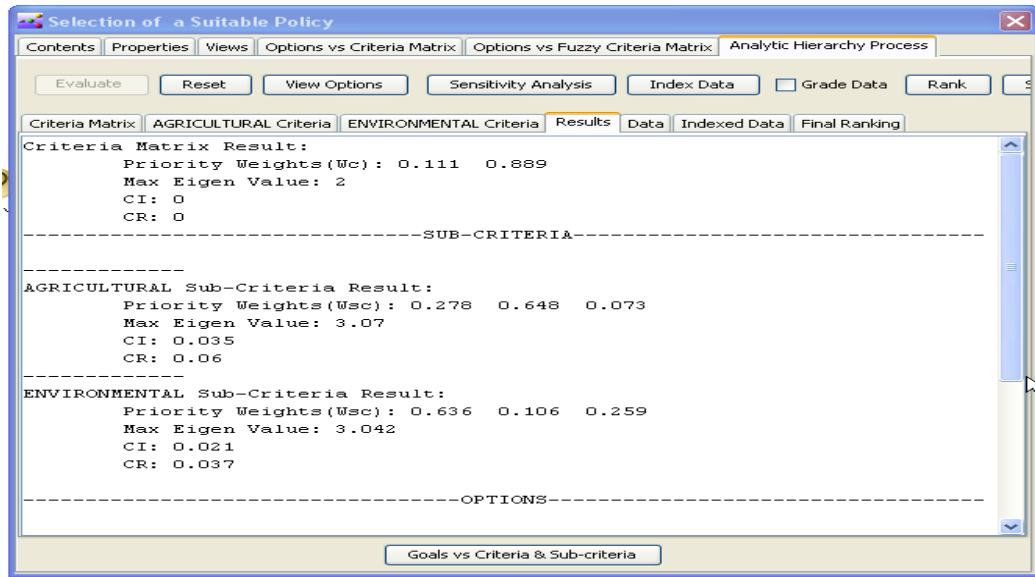


Figure 8.8: Priority Weights of Criteria and Options (Policies)

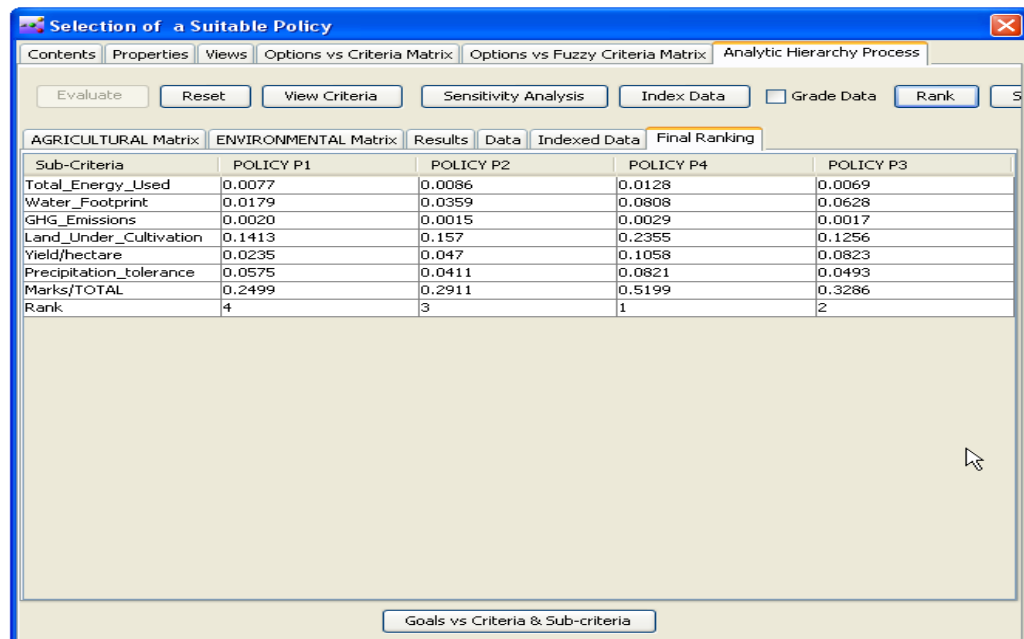


Figure 8.9: Ranking of Policies

According to AHP analysis of the policies, **policy P₄** of providing financial incentives to the farmers in the form of farm subsidies and provision of easy credit is found to be the best out of all policies options. This is because biofuels are usually not competitive (given their high production costs), financial incentives to the farmers such as provision of subsidy, margin money and easy loans need to be instituted to stimulate the demand for biofuels (Peters and Thielmann, 2008). The Government should act mainly as a facilitator providing policy support and interventions / incentives in critical areas.

Second Forward Process

This forecasting is done to test the effectiveness and impact of the first ranked policy P₄ selected from the first backward forecasting process on stakeholder preference of options. The second forecasting will seek to incorporate the stakeholders' preference of one option over the other in the context of adoption of policy P₄ in future. AHP is performed on a four-level hierarchy. The first level comprises the desired future scenario, the second level has two criteria, namely status quo and the predicted future, while the environmental and agricultural criteria form the third level of hierarchy, and the bottom level has 7 crops as options (seen in Figure 8.10).

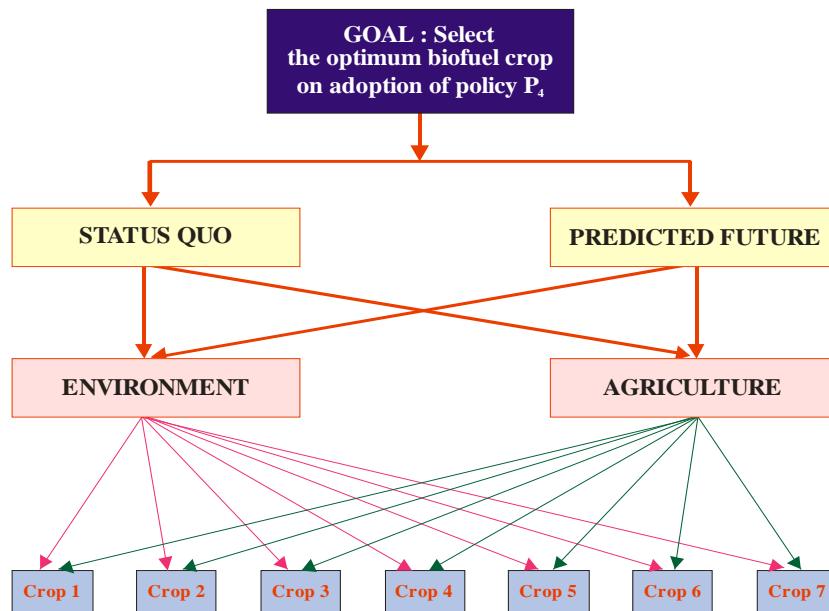


Figure 8.10: Selection of optimum bio fuel crop on adoption of policy P₄

The AHP analysis is carried out on the hierarchy shown in Figure 8.10, and the details are depicted in the following Figure 8.11.

TESTING THE EFFICACY OF THE SELECTED POLICY- P₄

Contents Properties Views Options vs Criteria Matrix Options vs Fuzzy Criteria Matrix Analytic Hierarchy Process

Evaluate Reset View Options Sensitivity Analysis Index Data Grade Data Rank Save Data

| Criteria Matrix | STAUTS_QUO Criteria | DESIRED_FUTURE_SCENARIO Criteria | Results | Data | Indexed Data | Graded Data | Final Ranking |
|--------------------|---------------------|----------------------------------|--------------|--------|--------------|-------------|---------------|
| Sub-Criteria | SUNFLOWER | SUGARCANE | SWEET SOR... | MAIZE | RAPESEED | SOYBEAN | JATROPHA |
| Environmental... | 0.8347 | 1.4607 | 0.626 | 0.4173 | 0.8347 | 0.2087 | 1.8781 |
| Agricultural_Co... | 3.1301 | 8.3471 | 4.1734 | 5.217 | 6.2602 | 2.0868 | 9.3904 |
| Environmental... | 0.6067 | 1.0616 | 0.455 | 0.3033 | 0.6067 | 0.1517 | 1.365 |
| Agricultural_Co... | 0.0746 | 0.199 | 0.0995 | 0.1244 | 0.1492 | 0.0497 | 0.2239 |
| Marks/TOTAL | 4.6461 | 11.0684 | 5.3539 | 6.062 | 7.8508 | 2.4969 | 12.8574 |
| Rank | 6 | 2 | 5 | 4 | 3 | 7 | 1 |

Goals vs Criteria & Sub-criteria

Figure 8.11: New Ranking of Crops on Implementing Policy P₄

If one now compares the total scores achieved by the two crop options of interest (sugarcane, jatropha) after implementing the policy P₄ with that of their original score (Figure 7.7) before implementing the policy P₄, it is seen that the Jatropha score has increased sharply but the sugarcane score has dropped only marginally.

| Iteration | SUGARCANE | JATROPHA |
|---|------------------|-----------------|
| AHP for current scenario (from Figure 7.7) | 12.272 | 4.3986 |
| Second Forward Iteration (from Figure 8.11) | 11.068 | 12.857 |

Table 8.2: Forward-Backward Forecasting Analysis

This small change in preference indicates that the policy P₄ is not sufficient to shift the stakeholders' preference to Jatropha. This policy needs to be implemented in conjunction with some other policy to reach the desired scenario of increasing the plantation of Jatropha. Such combination of policies can be pinpointed through sensitivity analysis and scenario planning. The users can go on carrying out numerous forward-backward iterations thereby allowing for inclusion of newer policies, pinpointing the best combinations of policies to obtain the desired result.

To conclude, what we observe is that the scenario planning technique provides us with a rational way of considering the future, not through the guesswork of predictions, but through testing the consequences of our actions and decisions in the context of different and distinct possible future (Darton, 2003). Decision-makers can play out the possibilities of given decision policies and examine their long term effects (Bohensky, 2006) on the overall objective. In this process, AHP plays a useful role in facilitating the introduction of quantitative comparisons to the analysis of options.

CHAPTER 9: SELECTING APPROPRIATE BIOFUEL CROP FOR CULTIVATION USING FUZZY AHP

Crop selection is an important part of a long-term conservation and sustainability strategy in agro-ecological systems. At the same time, the food deficit is increasing as a result of increase in the population, more so in developing and under-developed countries (Demirel et al. 2009). In this scenario, suitable crop selection is a prerequisite for sustainable agricultural cultivation of biofuel crops . It involves the evaluation of myriad criteria such as soil, terrain, water, and of course incorporation of the stakeholders' viewpoint along with experts' knowledge.

Chapter 7 described the implementation of the AHP methodology to analyse the most appropriate biofuels crop for cultivation in a given region. However, during the process of collecting the actual data, it becomes clear that the data are not very precise. In fact the data are seldom available as single value, but are more commonly in the form of ranges of values. Thus they can be truly recorded using linguistic variables such as LOW, MEDIUM as shown in Figure 9.1, where each linguistic descriptor characterizes a particular range.

| Criteria-L | Sugarcane-L | Sweet Sorghum-L | Jatropha-L | Soybean-L | Sunflower-L | Rapeseed-L | Maize-L |
|------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|
| Land_under_cultivation | LOW - (3.66,3.93,4.2) | VERY_HIGH - (29.03,29.0... | VERY_LOW - (0.4,0.43,0... | MEDIUM - (7.57,7.64,7.71) | LOW - (2.17,2.26,2.34) | MEDIUM - (7.28,7.37,7.32) | MEDIUM - (7.43,7.51,7.59) |
| Yield/hectare | VERY_HIGH - (647.0,658... | HIGH - (115.0,116.0,117.0) | VERY_HIGH - (375.0,375... | LOW - (90.8,99.05,107.3) | HIGH - (549.0,582.0,615.0) | LOW - (103.8,107.75,111.7) | MEDIUM - (190.7,192.25,... |
| Precipitation | VERY_HIGH - (4.7,23.8,4... | HIGH - (2.0,11.7,21.4) | VERY_LOW - (3.0,6.5,10.0) | LOW - (3.1,22.1,41.1) | HIGH - (2.0,21.0,40.0) | LOW - (3.0,15.5,28.0) | LOW - (2.3,21.7,41.1) |
| Water_Requirements | VERY_HIGH - (750.0,874... | HIGH - (400.0,575.0,750.0) | HIGH - (300.0,649.5,999.0) | HIGH - (600.0,600.0,600.0) | MEDIUM - (550.0,550.0,5... | VERY_LOW - (80.0,160.0,... | HIGH - (550.0,650.0,750.0) |
| soil_pH | HIGH - (4.3,6.35,8.4) | VERY_HIGH - (4.9,6.55,8.2) | MEDIUM - (5.0,6.0,7.0) | HIGH - (4.3,6.35,8.4) | HIGH - (4.5,6.6,8.7) | LOW - (4.2,4.5,4.8) | HIGH - (4.3,6.5,8.7) |
| Produce | VERY_HIGH - (237.08,259... | HIGH - (33.44,33.75,34.07) | VERY_LOW - (0.0,0.5,1.0) | LOW - (6.87,7.57,8.27) | LOW - (1.19,1.21,1.24) | LOW - (7.59,7.86,8.13) | MEDIUM - (14.17,14.44,1... |
| Nitrogen_Fertilizers | VERY_LOW - (0.0,0.5,1.0) | VERY_LOW - (0.0,0.5,1.0) | VERY_LOW - (0.0,0.5,1.0) | LOW - (0.0,3.8,7.6) | LOW - (5.3,7.25,9.2) | MEDIUM - (4.6,6.9,9.2) | VERY_LOW - (0.0,0.5,1.0) |
| Cetane_Number | LOW - (8.0,8.5,9.0) | LOW - (8.0,8.5,9.0) | VERY_HIGH - (46.0,58.0,... | HIGH - (53.0,53.0,53.0) | HIGH - (52.0,52.0,52.0) | HIGH - (55.0,56.5,58.0) | HIGH - (53.0,53.0,53.0) |
| Todine_Number | VERY_LOW - (0.0,0.5,1.0) | VERY_LOW - (0.0,0.5,1.0) | HIGH - (60.0,97.5,135.0) | VERY_HIGH - (125.0,132... | HIGH - (125.0,130.0,135.0) | MEDIUM - (97.0,106.0,11... | MEDIUM - (115.0,119.5,1... |
| Cloud_Point | VERY_LOW - (-22.0,-15.0... | LOW - (-16.0,-13.5,-11.0) | LOW - (-16.0,-13.5,-11.0) | LOW - (-16.0,-13.5,-11.0) | LOW - (-16.0,-13.5,-11.0) | LOW - (-16.0,-13.5,-11.0) | VERY_LOW - (-22.0,-15.0... |
| Flash_Point | HIGH - (122.0,122.0,122.0) | VERY_LOW - (13.0,13.0,1... | HIGH - (122.0,122.0,122.0) | HIGH - (122.0,122.0,122.0) | HIGH - (122.0,122.0,122.0) | HIGH - (122.0,122.0,122.0) | VERY_LOW - (13.0,13.0,1... |
| Pour_Point | VERY_LOW - (-117.3,-117... | VERY_LOW - (-117.3,-117... | MEDIUM - (9.0,9.0,9.0) | MEDIUM - (9.0,9.0,9.0) | MEDIUM - (9.0,9.0,9.0) | MEDIUM - (9.0,9.0,9.0) | VERY_LOW - (-117.3,-117... |
| Heat_of_Combustion | HIGH - (39.6,39.6,39.6) | MEDIUM - (27.0,27.0,27.0) | HIGH - (39.6,39.6,39.6) | HIGH - (39.6,39.6,39.6) | HIGH - (39.6,39.6,39.6) | HIGH - (39.6,39.6,39.6) | MEDIUM - (27.0,27.0,27.0) |
| Oil_Content | HIGH - (80.0,80.0,80.0) | LOW - (25.0,30.0,35.0) | MEDIUM - (43.0,51.0,59.0) | VERY_LOW - (18.0,20.0,2... | MEDIUM - (40.0,44.0,48.0) | LOW - (35.0,37.5,40.0) | HIGH - (75.0,75.0,75.0) |
| Oil_Yield | VERY_HIGH - (505.2,505... | VERY_HIGH - (600.0,600... | VERY_LOW - (189.2,189... | MEDIUM - (446.0,456.0,4... | LOW - (95.2,95.2,95.2) | LOW - (119.0,119.0,119.0) | VERY_LOW - (17.2,17.2,1... |
| Total_Energy_Obtained | VERY_HIGH - (139.0,139... | MEDIUM - (42.5,42.5,42.5) | MEDIUM - (49.9,49.9,49.9) | LOW - (31.9,31.9,31.9) | HIGH - (59.7,59.7,59.7) | MEDIUM - (41.7,41.7,41.7) | VERY_LOW - (0.0,0.5,1.0) |
| Total_Energy_Input | VERY_LOW - (0.0,0.5,1.0) | LOW - (15.0,32.5,50.0) | VERY_LOW - (0.0,0.5,1.0) | VERY_LOW - (15.0,25.0,3... | MEDIUM - (20.0,29.0,38.0) | LOW - (13.0,25.0,37.0) | HIGH - (25.0,32.5,40.0) |
| Water_Footprint | VERY_LOW - (108.0,108... | HIGH - (419.0,419.0,419.0) | VERY_HIGH - (574.0,574... | LOW - (177.0,177.0,177.0) | VERY_LOW - (0.0,0.5,1.0) | MEDIUM - (165.0,165.0,1... | VERY_LOW - (110.0,110... |
| Energy_Balance | MEDIUM - (3.2,3.2,3.2) | VERY_LOW - (0.0,0.5,1.0) | VERY_LOW - (0.0,0.5,1.0) | MEDIUM - (3.0,3.0,3.0) | MEDIUM - (3.2,3.2,3.2) | LOW - (2.7,2.7,2.7) | LOW - (1.5,1.5,1.5) |

Figure 9.1: The Linguistic Expressions for the Data Ranges

Such linguistic uncertainties can be appropriately handled by fuzzy sets. For this reason it is reasonable to explore application of fuzzy set theory to provide of realistic boundaries to the actual data. This Chapter provides an application of fuzzy AHP to a multi-criteria decision making problem through a case study. Although the Options vs Fuzzy Criteria Matrix (Chapter 5) deals with such linguistic variables within the decision matrix, this capability is not available for the AHP functionality. Hence, in order to enhance the capability of the existing AHP software functionality within Compendium, a provision for fuzzy AHP within the existing AHP functionality is also added.

Fuzzy AHP is the fuzzy extension of AHP to efficiently handle the fuzziness involved in the data of the decision-making. It is easier to understand, and it can effectively

handle both qualitative and quantitative data in multi-attribute decision-making problems.

There is a large body of literature dealing with applications of fuzzy AHP. A number of methods have been developed to handle fuzzy comparison matrices. For example, Van Laarhoven and Pedrycz (1983) suggested a fuzzy logarithmic least squares method (LLSM) to obtain triangular fuzzy weights from a triangular fuzzy comparison matrix. Wang et al. (2006) presented a modified fuzzy LLSM. Buckley (1985) utilized the geometric mean method to calculate fuzzy weights. Chang (1996) proposed an extent analysis, which derives crisp weights for fuzzy comparison matrices. Xu (2000) suggested a fuzzy least squares priority method (LSM). These methods are systematic approaches to the alternative selection and justification problem by using the concepts from fuzzy set theory and hierarchical structure analysis. However, only the method proposed by Chang(1996) offers the ability to quantify the data ranges in a manner appropriate for the present AHP technique. Decision-makers may find themselves more confident in giving interval judgments than fixed value judgments due to the fuzzy nature of the comparison process (Kharman et al, 2004).

The present approach uses triangular fuzzy numbers (TFNs) for preferences of one criterion over another. For this, the collected data is first converted into TFNs where the data range (x to y) is treated as a TFN, (x, m, y) , $m = (x + y)/2$. The data conversion display is shown in Figure 9.2. A crisp number, 'a' is treated as a TFN by taking it as (a, a, a) . By using the extent analysis method, the synthetic extent values of the pairwise comparison are calculated.

The methodology used for incorporating fuzzy AHP herein is known as **extent analysis** introduced by Chang (1996). It makes use of fuzzy data set and fuzzy weights. The preference for criteria is expressed between a range of values rather than the 9 point Saaty scale. The vagueness and uncertainty of the data used render the pairwise comparison of the classical AHP insufficient when it comes to expressing the relative importance of one criterion over another. Hence, in the face of such uncertainty, a fuzzy pairwise comparison scale is now required (Kwong and Bai, 2002). One such scale has been listed in Chapter 3, Table 3.3. The same in the present case study while doing pairwise comparison in fuzzy sense.

9.1. The Case Study

The application deals with the selection of the most appropriate biofuel crop for cultivation in a particular region characterized by different agricultural and technical diversity (Appendix 2). The problem is first modelled in a hierarchical manner similar to the one described and depicted in Chapter 7. However, its necessary to collect data for the region under consideration pertaining to various biofuel crops options accords to the different sub-criteria. This has been included in Appendix 2. The steps laid down in the extent analysis procedure are described in Section 3.3 in Chapter 3.

The hierarchy has four levels. The second level of hierarchy contains 3 criteria, namely, environmental, agriculture and technical. The fuzzy comparison matrix is then generated using the fuzzy comparison measures described in Table 3.3, and the results are shown in Figure 9.2.

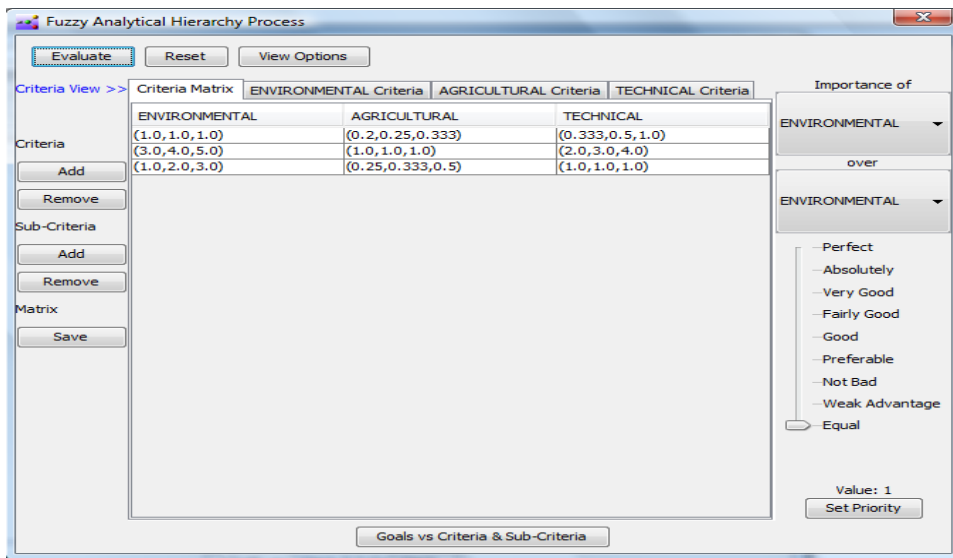


Figure 9.2: Fuzzy Comparison Matrix at Level 1 of Hierarchy

A similar comparison analysis has been carried out at level three between the sub-criteria constituting environment (8 sub-criteria), agriculture (7 sub-criteria), and technical (6 sub-criteria). The results are respectively depicted in Figures 9.3, 9.4, and 9.5. These Figures also depict the various constituents forming various sub-criteria at level three in the hierarchy.

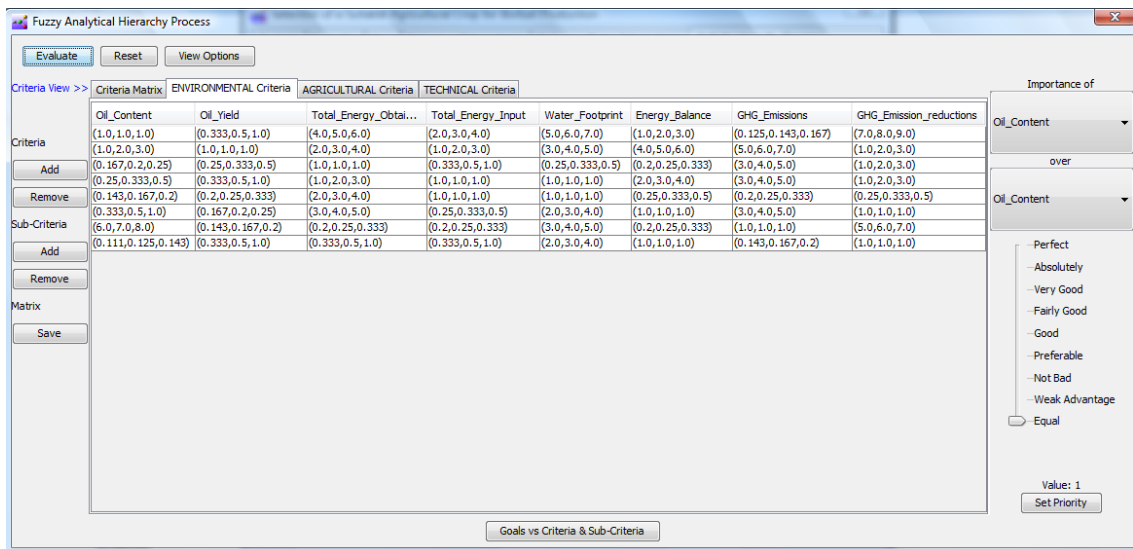


Figure 9.3: Fuzzy Comparison Matrix for Environment Sub-Criteria

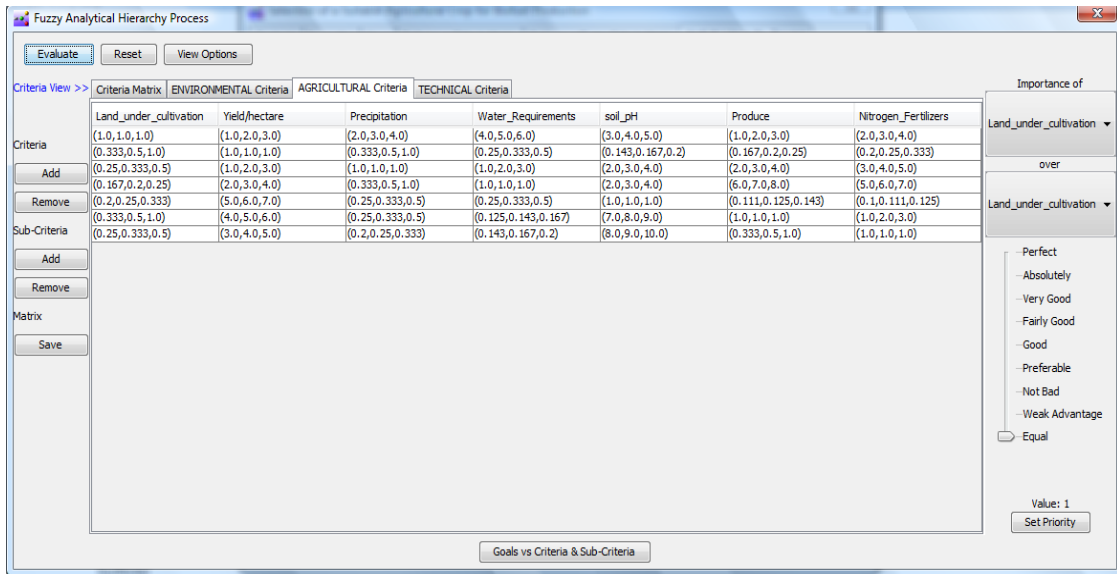


Figure 9.4: Fuzzy Comparison Matrix for Agriculture Sub-Criteria

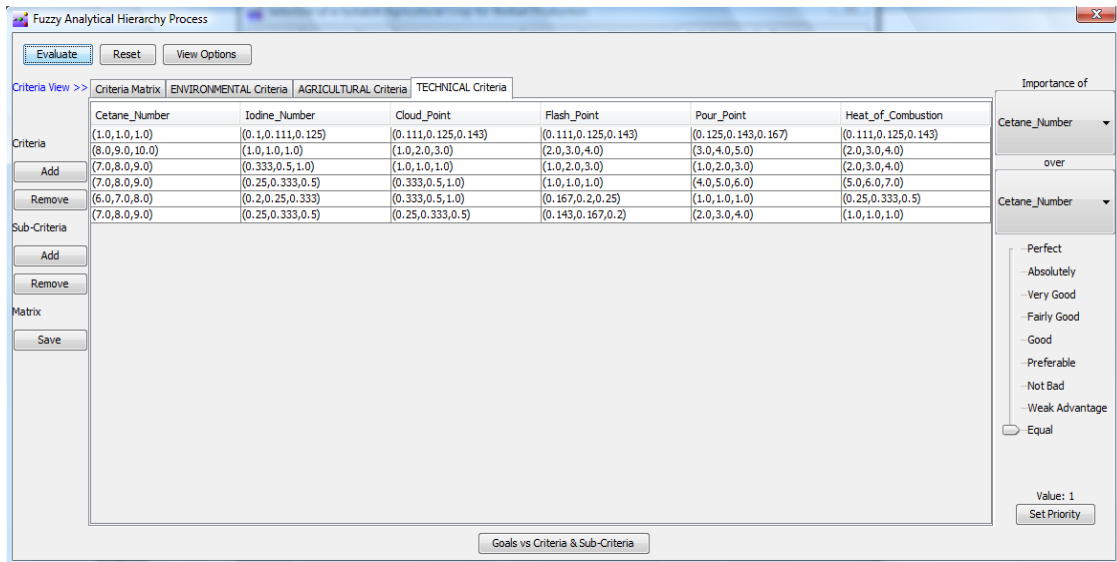


Figure 9.5: Fuzzy Comparison Matrix for Technical Sub-Criteria

Next, consider the last and fourth level of the hierarchy wherein 7 alternative biofuel crops are required to be ranked in order to choose the most appropriate biofuel crop for cultivation in the geographical region of India. Again a fuzzy comparison matrix is developed for choosing between the 7 competitive crops on the fuzzy AHP scale. The resultant fuzzy comparison matrix is shown in Figure 9.6.

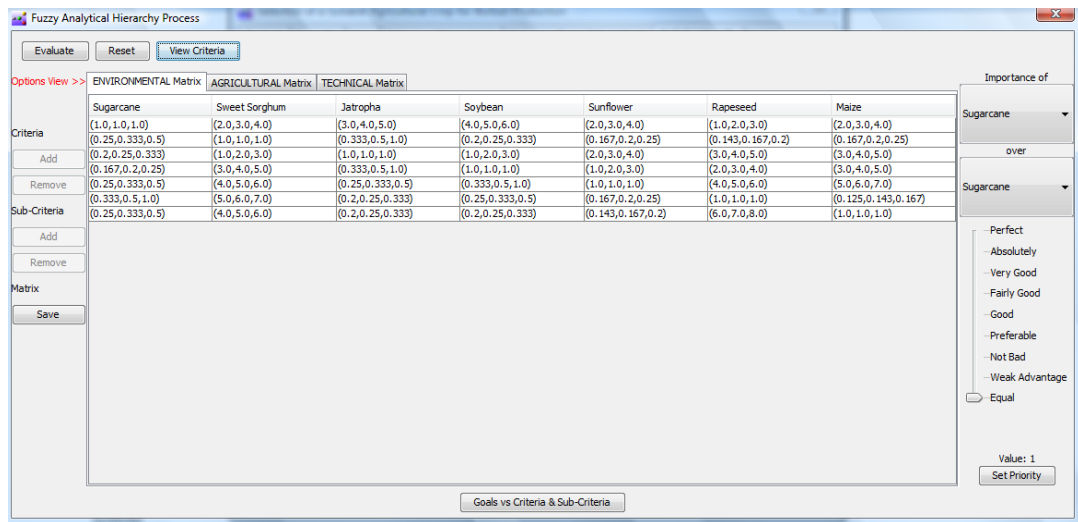


Figure 9.6: Fuzzy Comparison Matrix for Options

The priority vector (or weights) for each comparison matrix is generated by making use of the mathematical expressions described in steps b) and c) in the extent analysis procedure in Section 3.3, Chapter 3. The results are listed in Figure 9.7.

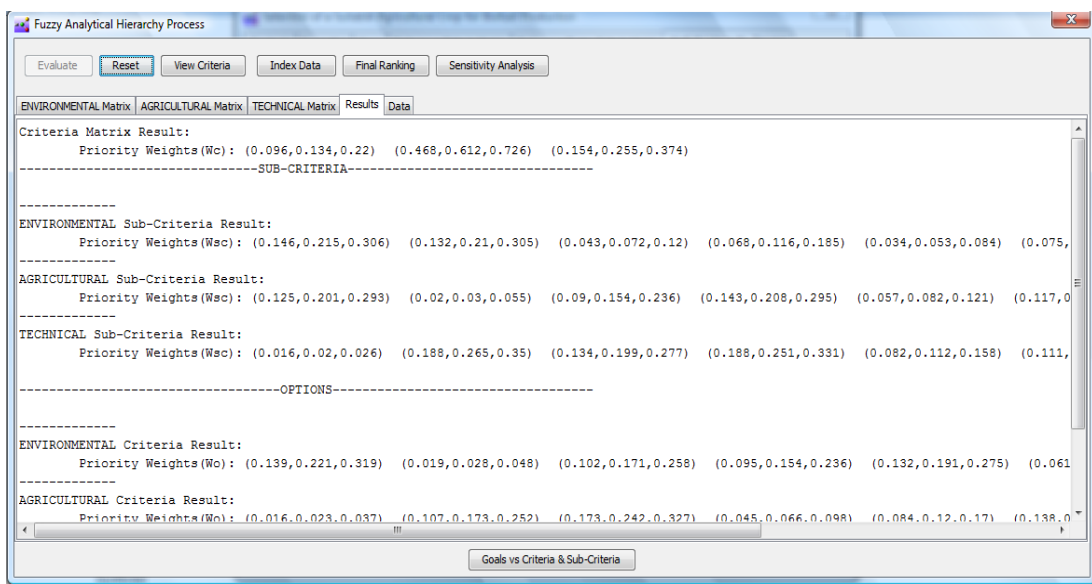


Figure 9.7: Priority Vectors for Three Levels of Hierarchy

The priority vectors or weights of the all levels are aggregated to generate the global weights of the options. The aggregation procedure is simple and already explained in section 3.3. In this way the matrix of priority vectors is generated for the options. The order of the matrix is 21 x 7, where the 21 sub-criteria form the rows while the 7

biofuel crops options are represented in the 7 columns of this matrix. Note that each entry in the priority weight matrix is a TFN. Simultaneously, it is necessary to work with actual data for the region concerning the 7 crops options and all the considered sub-criteria (Appendix 2). The data are first indexed using sugarcane as the base option. For the purpose of conditioning the data, indexing is carried out using the rules of fuzzy division listed in Table 9.2. Table 9.1 shows how the fuzzy data are generally represented.

| | | | |
|----------------------------|----------------------------|-------|----------------------------|
| (a_{11}, b_{11}, c_{11}) | (a_{12}, b_{12}, c_{12}) | ..... | (a_{1n}, b_{1n}, c_{1n}) |
| (a_{21}, b_{21}, c_{21}) | (a_{22}, b_{22}, c_{22}) | ..... | (a_{2n}, b_{2n}, c_{2n}) |
| | | | |
| (a_{m1}, b_{m1}, c_{m1}) | (a_{m2}, b_{m2}, c_{m2}) | ..... | (a_{mn}, b_{mn}, c_{mn}) |

Table 9.1: General Form of a Fuzzy Data Table

For indexing the actual data, the middle element in the first cell of each row is regarded as the base and the rest of the elements in the row are divided by it to generate the ratio scales using the principle of fuzzy division (Kaufmann and Gupta, 1991). The principle is shown in Table 9.2.

| | | | |
|---|---|-------|---|
| $\frac{a_{11}}{b_{11}}, \frac{b_{11}}{b_{11}}, \frac{c_{11}}{b_{11}}$ | $\frac{a_{12}}{b_{11}}, \frac{b_{12}}{b_{11}}, \frac{c_{12}}{b_{11}}$ | ----- | $\frac{a_{1n}}{b_{11}}, \frac{b_{1n}}{b_{11}}, \frac{c_{1n}}{b_{11}}$ |
| $\frac{a_{21}}{b_{21}}, \frac{b_{21}}{b_{21}}, \frac{c_{21}}{b_{21}}$ | $\frac{a_{22}}{b_{21}}, \frac{b_{22}}{b_{21}}, \frac{c_{22}}{b_{21}}$ | ----- | $\frac{a_{2n}}{b_{21}}, \frac{b_{2n}}{b_{21}}, \frac{c_{2n}}{b_{21}}$ |
| ----- | ----- | ----- | ----- |
| $\frac{a_{m1}}{b_{m1}}, \frac{b_{m1}}{b_{m1}}, \frac{c_{m1}}{b_{m1}}$ | $\frac{a_{m2}}{b_{m1}}, \frac{b_{m2}}{b_{m1}}, \frac{c_{m2}}{b_{m1}}$ | ----- | $\frac{a_{mn}}{b_{m1}}, \frac{b_{mn}}{b_{m1}}, \frac{c_{mn}}{b_{m1}}$ |

Table 9.2: Fuzzy Division in Indexing Procedure

The result of indexing the actual data are shown in Figure 9.8.

| Criteria | Sugarcane | Sweet Sorghum | Jatropha | Soybean | Sunflower | Rapeseed | Maize |
|-------------------------|-------------------|---------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| Land_under_cultivation | (0.931,1.0,1.069) | (7.387,7.389,7.389) | (0.102,0.109,0.115) | (1.926,1.944,1.962) | (0.552,0.575,0.595) | (1.852,1.858,1.863) | (1.891,1.911,1.931) |
| Yield/hectare | (0.983,1.0,1.017) | (0.175,0.176,0.178) | (0.57,0.57,0.57) | (0.138,0.151,0.163) | (0.834,0.884,0.935) | (0.158,0.164,0.17) | (0.29,0.292,0.295) |
| Precipitation | (0.197,1.0,1.803) | (0.084,0.492,0.899) | (0.126,0.273,0.42) | (0.13,0.929,1.727) | (0.084,0.882,1.681) | (0.126,0.651,1.176) | (0.097,0.912,1.727) |
| Water_Requirements | (0.858,1.0,1.142) | (0.457,0.658,0.858) | (0.343,0.743,1.142) | (0.686,0.686,0.686) | (0.629,0.629,0.629) | (0.091,0.183,0.274) | (0.629,0.743,0.858) |
| soil_pH | (0.677,1.0,1.323) | (0.772,1.031,1.291) | (0.787,0.945,1.102) | (0.677,1.0,1.323) | (0.709,1.039,1.37) | (0.661,0.709,0.756) | (0.677,1.024,1.37) |
| Produce | (0.915,1.0,1.085) | (0.129,0.13,0.131) | (0.0,0.0020,0.0040) | (0.027,0.029,0.032) | (0.0050,0.0050,0.0050) | (0.029,0.03,0.031) | (0.055,0.056,0.057) |
| Nitrogen_Fertilizers | (0.0,1.0,2.0) | (0.0,1.0,2.0) | (0.0,1.0,2.0) | (0.0,7.6,15.2) | (10.6,14.5,18.4) | (9.2,13.8,18.4) | (0.0,1.0,2.0) |
| Cetane_Number | (0.941,1.0,1.059) | (0.941,1.0,1.059) | (5.412,6.824,8.235) | (6.235,6.235,6.235) | (6.118,6.118,6.118) | (6.471,6.647,6.824) | (6.235,6.235,6.235) |
| Iodine_Number | (0.0,1.0,2.0) | (0.0,1.0,2.0) | (120.0,195.0,270.0) | (250.0,265.0,280.0) | (250.0,260.0,270.0) | (194.0,212.0,230.0) | (230.0,239.0,248.0) |
| Cloud_Point | (1.467,1.0,0.533) | (1.067,0.9,0.733) | (1.067,0.9,0.733) | (1.067,0.9,0.733) | (1.067,0.9,0.733) | (1.067,0.9,0.733) | (1.467,1.0,0.533) |
| Flash_Point | (1.0,1.0,1.0) | (0.107,0.107,0.107) | (1.0,1.0,1.0) | (1.0,1.0,1.0) | (1.0,1.0,1.0) | (1.0,1.0,1.0) | (0.107,0.107,0.107) |
| Pour_Point | (1.0,1.0,1.0) | (1.0,1.0,1.0) | (-0.077,-0.077,-0.077) | (-0.077,-0.077,-0.077) | (-0.077,-0.077,-0.077) | (-0.077,-0.077,-0.077) | (1.0,1.0,1.0) |
| Heat_of_Combustion | (1.0,1.0,1.0) | (0.682,0.682,0.682) | (1.0,1.0,1.0) | (1.0,1.0,1.0) | (1.0,1.0,1.0) | (1.0,1.0,1.0) | (0.682,0.682,0.682) |
| Oil_Content | (1.0,1.0,1.0) | (0.312,0.375,0.438) | (0.538,0.638,0.738) | (0.225,0.25,0.275) | (0.5,0.55,0.6) | (0.438,0.469,0.5) | (0.938,0.938,0.938) |
| Oil_Yield | (1.0,1.0,1.0) | (1.188,1.188,1.188) | (0.375,0.375,0.375) | (0.883,0.903,0.922) | (0.188,0.188,0.188) | (0.236,0.236,0.236) | (0.034,0.034,0.034) |
| Total_Energy_Obtained | (1.0,1.0,1.0) | (0.306,0.306,0.306) | (0.359,0.359,0.359) | (0.229,0.229,0.229) | (0.429,0.429,0.429) | (0.3,0.3,0.3) | (0.0,0.0040,0.0070) |
| Total_Energy_Input | (0.0,1.0,2.0) | (30.0,65.0,100.0) | (0.0,1.0,2.0) | (30.0,50.0,70.0) | (40.0,58.0,76.0) | (26.0,50.0,74.0) | (50.0,65.0,80.0) |
| Water_Footprint | (1.0,1.0,1.0) | (3.88,3.88,3.88) | (5.315,5.315,5.315) | (1.639,1.639,1.639) | (0.0,0.0050,0.0090) | (1.528,1.528,1.528) | (1.019,1.019,1.019) |
| Energy_Balance | (1.0,1.0,1.0) | (0.0,0.156,0.312) | (0.0,0.156,0.312) | (0.938,0.938,0.938) | (1.0,1.0,1.0) | (0.844,0.844,0.844) | (0.469,0.469,0.469) |
| GHG_Emissions | (0.5,1.0,1.5) | (0.0,0.062,0.125) | (0.0,0.062,0.125) | (6.125,6.125,6.125) | (0.0,0.062,0.125) | (4.625,4.625,4.625) | (10.125,10.375,10.625) |
| GHG_Emission_reductions | (1.0,1.0,1.0) | (0.0,0.294,0.588) | (0.0,0.294,0.588) | (1.406,1.406,1.406) | (0.0,0.294,0.588) | (1.7,1.7,1.7) | (0.665,0.665,0.665) |

Figure 9.8: Fuzzy Indexed Data

Finally, the column of the indexed data matrix is multiplied with the corresponding column of the priority vectors matrix to generate the overall score of the 7 crops options.

The multiplication of two vectors $((a_1, b_1, c_1), \dots, (a_n, b_n, c_n))$ and $((x_1, y_1, z_1), \dots, (x_n, y_n, z_n))$ with fuzzy entries is to be understood as a TFN

$$\left(\sum_{i=1}^n a_i x_i, \sum_{i=1}^n b_i y_i, \sum_{i=1}^n c_i z_i \right).$$

The fuzzy scores so obtained are defuzzified using the centroid method, which is described by averaging out the TFN, say (a, b, c) by $(a + b + c)/3$. These defuzzified numbers are shown in Figure 9.9. Subsequently on summing these; the final ranking of the crops is obtained. The crop with the highest total score is adjudged first rank. The other ranks are given in descending order of crisp total scores.

| Sub-Criteria | Sugarcane | Sweet Sorghum | Jatropha | Soybean | Sunflower | Rapeseed | Maize |
|-------------------------|-----------|---------------|------------|------------|------------|------------|------------|
| Land_under_cultivation | 0.00542 | 0.0388 | 5.8594 E-4 | 0.0102 | 0.0030 | 0.0097 | 0.0100 |
| Yield/hectare | 0.00517 | 9.0912 E-4 | 0.0029 | 8.0546 E-4 | 0.0046 | 8.5638 E-4 | 0.0015 |
| Precipitation | 0.00277 | 0.0013 | 6.8041 E-4 | 0.0026 | 0.0025 | 0.0018 | 0.0026 |
| Water_Requirements | 0.00322 | 0.0022 | 0.0028 | 0.0020 | 0.0018 | 5.9691 E-4 | 0.0024 |
| soil_pH | 0.00160 | 0.0016 | 0.0014 | 0.0016 | 0.0016 | 0.0010 | 0.0016 |
| Produce | 0.00312 | 3.9170 E-4 | 8.7833 E-6 | 9.1636 E-5 | 1.4167 E-5 | 9.2397 E-5 | 1.6838 E-4 |
| Nitrogen_Fertilizers | 0.00579 | 0.0057 | 0.0057 | 0.0440 | 0.0639 | 0.0625 | 0.0057 |
| Cetane_Number | 0.00160 | 0.0016 | 0.0118 | 0.0097 | 0.0095 | 0.0105 | 0.0097 |
| Iodine_Number | 0.01926 | 0.1386 | 0.0020 | 0.0366 | 0.0109 | 0.0348 | 0.0360 |
| Cloud_Point | 0.00321 | 5.6439 E-4 | 0.0018 | 4.9813 E-4 | 0.0028 | 5.3887 E-4 | 9.3514 E-4 |
| Flash_Point | 0.01957 | 0.0097 | 0.0049 | 0.0185 | 0.0178 | 0.0127 | 0.0183 |
| Pour_Point | 0.02044 | 0.0141 | 0.0172 | 0.0133 | 0.0122 | 0.0042 | 0.0152 |
| Heat_of_Combustion | 0.00877 | 0.0088 | 0.0078 | 0.0087 | 0.0091 | 0.0056 | 0.0090 |
| Oil_Content | 0.01661 | 0.0021 | 4.2536 E-5 | 4.8668 E-4 | 7.6016 E-5 | 4.9486 E-4 | 9.0396 E-4 |
| Oil_Yield | 0.01969 | 0.0196 | 0.0196 | 0.1497 | 0.2305 | 0.2239 | 0.0196 |
| Total_Energy_Obtained | 8.31032 | 0.0059 | 8.9807 E-5 | 0.0015 | 4.7106 E-4 | 0.0015 | 0.0015 |
| Total_Energy_Input | 0.01891 | 0.0019 | 0.0061 | 0.0016 | 0.0098 | 0.0018 | 0.0031 |
| Water_Footprint | 0.01150 | 0.0057 | 0.0028 | 0.0108 | 0.0105 | 0.0075 | 0.0108 |
| Energy_Balance | 0.01095 | 0.0076 | 0.0094 | 0.0070 | 0.0064 | 0.0022 | 0.0081 |
| GHG_Emissions | 0.00548 | 0.0054 | 0.0048 | 0.0054 | 0.0056 | 0.0034 | 0.0056 |
| GHG_Emission_reductions | 0.00671 | 8.4608 E-4 | 1.8199 E-5 | 1.9695 E-4 | 3.0575 E-5 | 1.9927 E-4 | 3.6350 E-4 |
| Marks/TOTAL | 0.18272 | 0.2741 | 0.1032 | 0.3259 | 0.4038 | 0.3865 | 0.1638 |
| Rank | 5 | 4 | 7 | 3 | 1 | 2 | 6 |

Figure 9.9: Total Score and Final Ranking of Crops

The study indicates that **sunflower** is the most appropriate biofuel crop to be grown in the region; while rapeseed follows at second place. The analysis clearly indicates that by incorporating the choices of the stakeholders, even if the choices are not very precisely stated, the fuzzy AHP extent analysis provides a means of determining the most appropriate biofuel crop for the region.

It may be concluded that fuzzy AHP, allows effective representation of the uncertainty and vagueness of subjective perception in an analysis that will help decision makers reach a logical decision. The technique thus allows stakeholder preferences which may be fuzzy to be incorporated in addition to other fuzzy data.

9.2. Scenario Planning

After pinpointing the optimum crop for biofuel cultivation, there is a need to explore policies which can encourage the cultivation of the selected crop. As already described in Chapter 8, scenarios can contribute to the formation process of the sustainable policies. Broadly, the stages of scenario planning (Fahey and Randall, 1998) are:

- understanding the scenario context (in this case, formulation of policies encouraging sustainable biofuels crops cultivation);
- identifying and formulating alternatives (in this case the different policy alternatives);
- choosing among alternatives (the policy alternatives)
- evaluating the possible impact of executing the chosen alternative (policy).

In the present study, four policies are identified for further investigation. These are shown in Table 9.3, and have in common that they are designed to encourage sustainable land utilization for biofuels crop cultivation.

| | |
|-----------------------|---|
| Policy P ₁ | Provision of financial incentives to the farmers in the form of farm subsidies and availability of easy credit in order to encourage the cultivation of non-agricultural land |
| Policy P ₂ | Regulations of laws for land cover and usage, including fixing the land percentage to be devoted exclusively to food crop production, forests and pastures. |
| Policy P ₃ | Preparation of regulations for fertilizer production and usage of irrigation water |
| Policy P ₄ | Increasing productivity and diversification of agricultural production such that both food security and substantial biofuel cultivation can be achieved at the same time. |

Table 9.3: Possible Policies (adapted from Demirel et al., 2009)

In the context of the present case study, the aforementioned four policies are expected to serve as the pathways for achieving the future goal of cultivating the selected biofuels crop, (in this case, sunflower). The decision maker ascribes different relative weights to pairwise comparison matrix for each of the future policy scenarios. The fuzzy AHP has been used as a means of identifying a policy which can help achieve the desired scenario in some future year X. The fuzzy AHP functionality developed as an extension of the AHP has been used for this particular scenario planning case study.

A three-level hierarchy has been considered, where the first level comprises the goal of pinpointing the requisite policy for encouraging the cultivation of a given crop, the

second level comprises of the 3 clusters of criteria, viz., environmental, agricultural, and technological, while the third level comprises of the 4 policies being considered.

As shown in Figure 9.10, the preference of a given criterion over another is expressed in terms of the linguistic variables such as EQUAL. The linguistic variables are quantified using the 9 point fuzzified scale of Table 3.3 in Chapter 3, where their values lie between lower and upper extremities, and set at their requisite locations in the criteria matrix as TFNs.

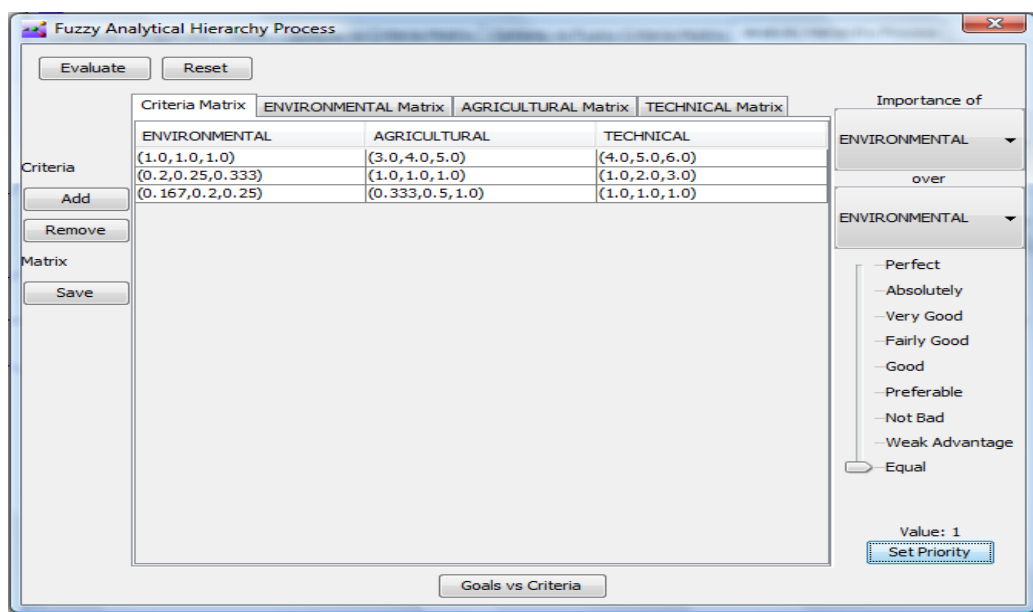


Figure 9.10: Criteria Matrix

Similarly, the preference for the policy options with respect to each of the criterion too is considered in Figure 9.11.

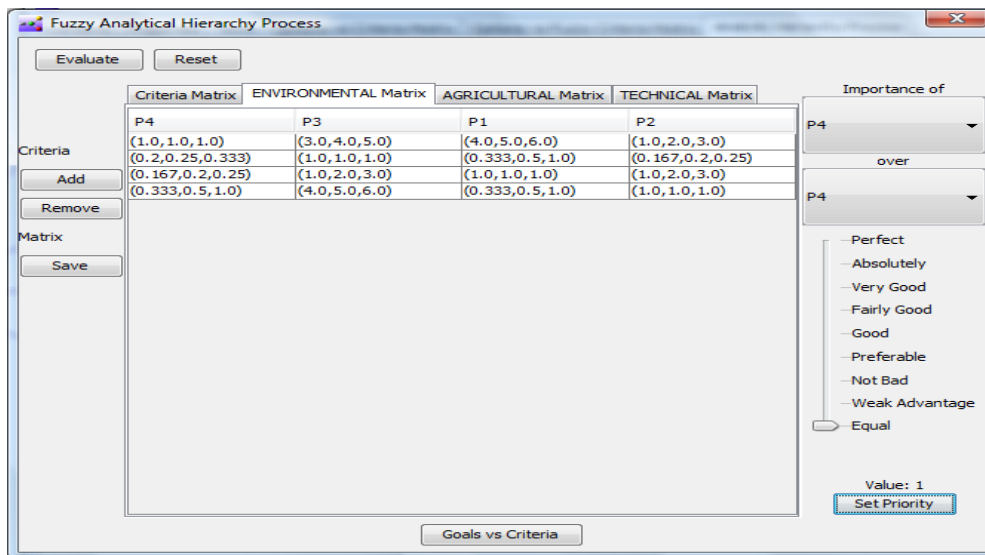


Figure 9.11: Preference for Options

The priority vectors are then calculated, and shown in Figure 9.12. This case does not consider the sub-criteria and whether to include them or not at the discretion of the user. In turn, these priority vectors in turn are used to rank the different policy options.

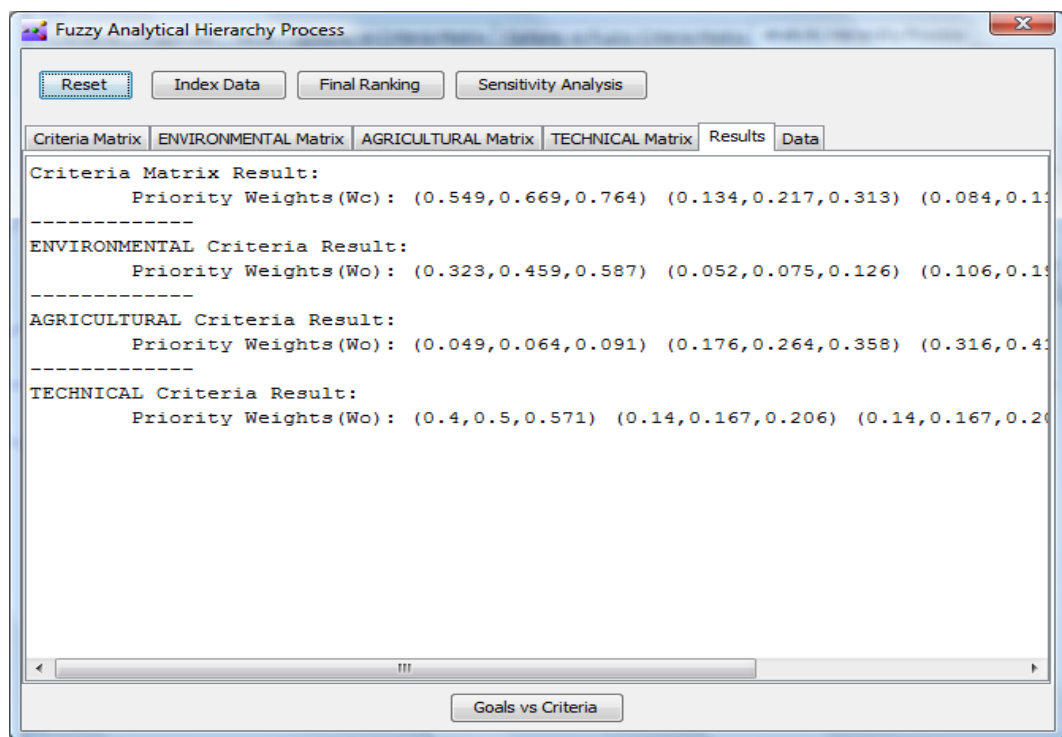


Figure 9.12: Priority Weights of Fuzzy Comparison Matrices at Both the Levels

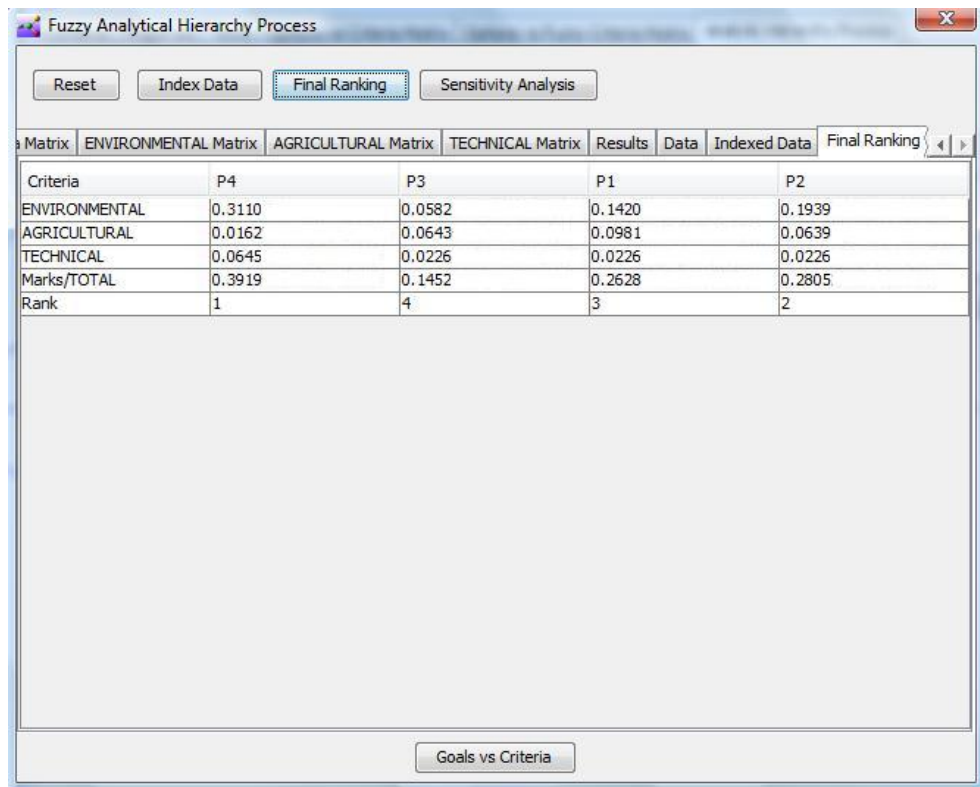


Figure 9.13: Ranking of Policies

From the Figure 9.13, policy **P₄**, the policy of “Increasing productivity and diversifying agricultural production such that both food security and substantial biofuel cultivation can be achieved at the same time” is regarded as best among all the policies considered in the context of selection of a suitable land utilization policy. In order to facilitate such study, a functionality namely fuzzy AHP functionality has been added within the AHP functionality in the Compendium software.

The scenario planning study performed using the fuzzy Analytical Hierarchy Process functionality can also be cross checked and validated by performing a graphical scenario planning (see Section 9.4).

9.3. Sensitivity Analysis

A sensitivity analysis has been performed to see the impact of stakeholder preferences on the selection of the policy options. by varying the priority weight of criteria.

According to Figure 9.14, a negative variation of 100% in the priority weight of the environmental criterion leads to the recommendation of P₁ as satisfying options. The negative variation in priority weight can be interpreted arising out of negative attitudes of the stakeholders and the subsequent criteria preferences in the context of their attitude.

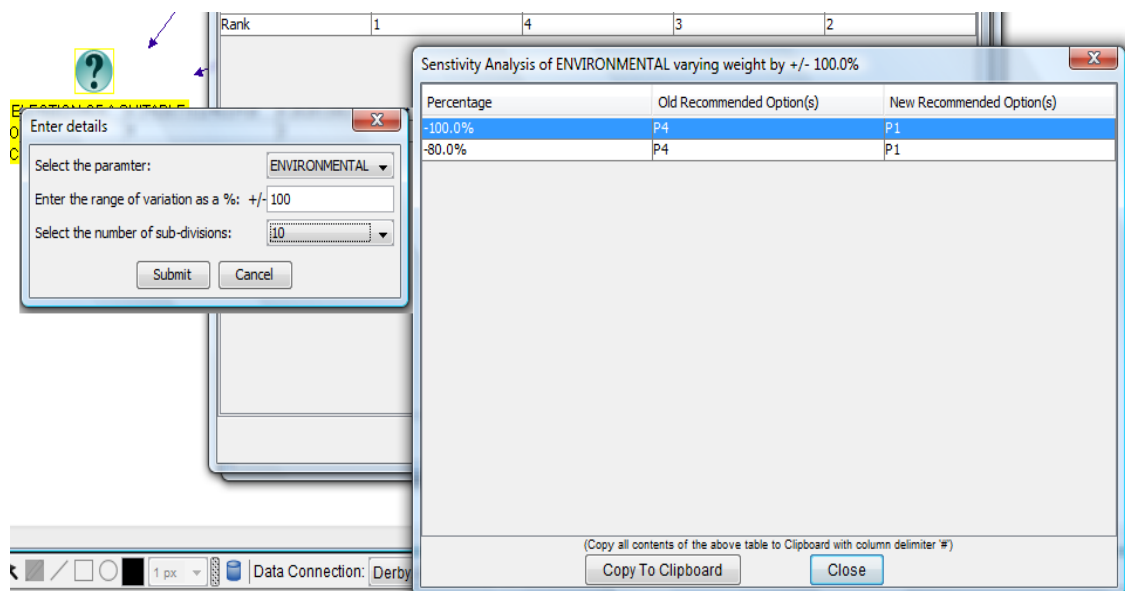


Figure 9.14: GUI of Sensitivity Analysis

Given that the present analysis deals with stakeholder preferences and uncertainty, this example is sufficient to demonstrate that a threshold/breakpoint of change exists wherein new options become suitable under the changed situation.

The results obtained in this section, will be graphically verified on the basis of the Deng's Performance Index in the section to follow.

9.4. Graphical Scenario Planning

The scenario planning study is performed using a graphical representation to analyze the impact of varying attitude either of stakeholders (which in this case will be reflected on the criteria) on ranking the policy options. The variation in stakeholders' attitude stem from certain changes in situations that may affect the criteria under consideration or it may be due to the imprecise or incomplete knowledge of the decision problem being tackled. Mathematically, the stakeholders' attitude can be expressed using two factors (Hsu, 1999):

- The degree of satisfaction with the given scenario (to be represented by α).
- Within the degree of satisfaction, the attitude of the stakeholder - pessimism or optimism with the scenario (to be represented by λ).

The value of α lies in $[0, 1]$, where $\alpha = 0$ and $\alpha = 1$ respectively signify the least and the greatest possible degree of satisfaction of the stakeholder (Pan, 2008). For instance, $\alpha = 0.8$ represents 80% satisfaction level of the stakeholder with the decision taken or option selected. To reflect a particular degree of satisfaction regarding the decision-making process, the notion of α -cut is applied. Variations in the values of the α -cut provide for the incorporation of the impact of stakeholder attitude within the study (Prakash, 2003).

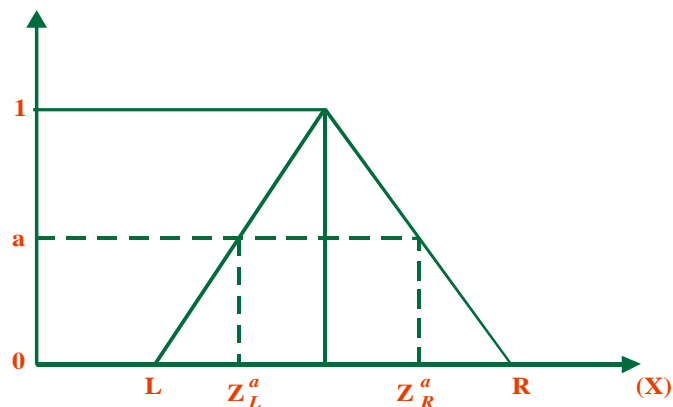


Figure 9.15: Triangular Fuzzy Interval Under α -cut (Pan, 2008)

For a given $\alpha \in (0, 1)$, the α -cut of a TFN, Z , is the interval $[Z_L^\alpha, Z_R^\alpha]$ as shown in Figure 9.15. Any point in this interval can be expressed as

$$Z_L^\alpha + \hat{\lambda} (Z_R^\alpha - Z_L^\alpha), \quad \text{for } \hat{\lambda} \in (0, 1), \quad (9.1)$$

where $\hat{\lambda}$ is the index of pessimism of the decision maker or the stakeholder. Here, $\hat{\lambda} = 0$ (i.e., Z_L^α), represents a situation of absolute optimism while $\hat{\lambda} = 1$ (i.e., Z_R^α) represents the situation of absolute pessimism regarding the stakeholder at the satisfaction level α .

Based on the priority weights of the criteria and options obtained (Figure 9.13), a matrix of criteria and policies is constructed known as the performance matrix, which represents the overall performance of all alternatives (here four policies) with respect to the three cluster criteria. A general form of a 4*3 performance matrix (Deng, 1999) is shown in Table 9.4.

| | Criteria C1 | Criteria C2 | Criteria C3 |
|------------------|--|--|--|
| Policy P1 | (a ₁₁ , b ₁₁ , c ₁₁) | (a ₁₂ , b ₁₂ , c ₁₂) | (a ₁₃ , b ₁₃ , c ₁₃) |
| Policy P2 | (a ₂₁ , b ₂₁ , c ₂₁) | (a ₂₂ , b ₂₂ , c ₂₂) | (a ₂₃ , b ₂₃ , c ₂₃) |
| Policy P3 | (a ₃₁ , b ₃₁ , c ₃₁) | (a ₃₂ , b ₃₂ , c ₃₂) | (a ₃₃ , b ₃₃ , c ₃₃) |
| Policy P4 | (a ₄₁ , a ₄₁ , a ₄₁) | (a ₄₂ , b ₄₂ , c ₄₂) | (a ₄₃ , b ₄₃ , c ₄₃) |

Table 9.4: TFN Performance Matrix Deng's Performance Index

Deng's Performance Index

To avoid the complex and unreliable process of comparing fuzzy utilities, Deng (1999) presented an approach for effectively solving qualitative multi-criteria problems based on fuzzy pairwise comparison. The α -cut concept is used to transform the fuzzy performance matrix representing the overall performance of all alternatives with respect to each criterion into an interval performance matrix. Incorporated with the decision makers' attitude towards risk, an overall performance index is obtained for each alternative across all criteria by applying the concept of the degree of similarity to the ideal solution using the vector matching function.

In what follows, we first describe the Deng's approach for performing a multi-criteria analysis and thereby ranking of various options (in our case, the four policies) in a problem of fuzzy AHP involving qualitative data. A full account of this has been given by Deng's (1999) work.

For a general TFN, say (a, b, c) , the α -interval of confidence (or α -cut) for $\alpha \in (0, 1)$ is given by

$$(a + \alpha(b-a), c - \alpha(c-b)) \quad (9.2)$$

Where a is the lowest possible value of the given TFN, b is the middle value and c is the highest possible value of TFN.

The α – cut is denoted by $[Z_L^\alpha, Z_R^\alpha]$, where,

$$Z_L^\alpha = a + \alpha(b - a) \quad Z_R^\alpha = c + \alpha(c - b) \quad (9.3)$$

The decision maker's degree of confidence in his fuzzy assessment regarding criterion weight is represented by α . A larger value of α indicates that the decision maker assessments are closer to the greatest possible degree of satisfaction (see Figure 9.15). Incorporating the decision maker attitude towards risk, a degree of pessimism is added in form of parameter $\lambda \in (0, 1)$. So, the risk attitude of the stakeholder at satisfaction level α is described by

$$Z_L^\alpha + \lambda (Z_R^\alpha - Z_L^\alpha), \quad \text{for } \lambda \in (0, 1). \quad (9.4)$$

Now for a given α , the interval performance matrix (A^α) is formulated as follows

| | Criteria C₁ | Criteria C₂ | Criteria C₃ |
|-----------------------------|------------------------------------|------------------------------------|------------------------------------|
| Policy P₁ | $(Z_{11L}^\alpha, Z_{11R}^\alpha)$ | $(Z_{12L}^\alpha, Z_{12R}^\alpha)$ | $(Z_{13L}^\alpha, Z_{13R}^\alpha)$ |
| Policy P₂ | ..... | ..... | ..... |
| Policy P₃ | ..... | ..... | ..... |
| Policy P₄ | $(Z_{41L}^\alpha, Z_{41R}^\alpha)$ | $(Z_{42L}^\alpha, Z_{42R}^\alpha)$ | $(Z_{43L}^\alpha, Z_{43R}^\alpha)$ |

Table 9.5: Interval Performance Matrix

To facilitate the vector matching process of Deng (1999), the value of $\alpha \in (0, 1)$ is fixed. By taking $\lambda = 0$ (which means absolute optimism), we formulate the crisp performance matrix A (with fixed α and $\lambda = 0$) from each interval's left entries in Table 9.6.

| | Criterion C₁ | Criterion C₂ | Criterion C₃ |
|-----------------------------|--------------------------------|--------------------------------|--------------------------------|
| Policy P₁ | Z_{11L}^α | Z_{12L}^α | Z_{13L}^α |
| Policy P₂ | ..... | ..... | ..... |
| Policy P₃ | ..... | ..... | ..... |
| Policy P₄ | Z_{41L}^α | Z_{42L}^α | Z_{43L}^α |

Table 9.6: Left Interval Performance Matrix for a Fixed α at $\lambda = 0$

In lines with the ideal solution concept, the positive and the negative ideal solutions of the above crisp version of the performance matrix are determined. For that, first determine the maximum and minimum values in each column across all the alternatives (in this case, four policies). The maximum and minimum values of the column provide the positive and negative ideal solutions which are denoted by A^+ and A^- respectively and are given by

$$A^+ = (Z_1^+, Z_2^+, Z_3^+) \quad A^- = (Z_1^-, Z_2^-, Z_3^-) \quad (9.5)$$

Here, Z_i^+ stands for the maximum value in the i^{th} column and Z_i^- stands for a minimum value in the i^{th} column ($i = 1, 2, 3$).

By applying the vector matching function, the degree of similarity between each alternative and the positive ideal solution and the negative ideal solution can be calculated.

For all rows ($i=1$ to 4, comprising of the policies), the synthetic values (S_i) are computed:

$$S_i^+ = \frac{A_i * A^+}{\max(A_i * A_i, A^+ * A^+)}, \quad S_i^- = \frac{A_i * A^-}{\max(A_i * A_i, A^- * A^-)}, \quad i = 1, \dots, 4.$$

where A_i stands for the i^{th} row of matrix \mathbf{A} .

The larger values of S_i^+ and S_i^- indicate the higher degree of similarity of alternative A_i 's performance to that of the positive ideal solution and the negative ideal solution respectively (Deng, 1999). The overall performance index (PI) for each of the alternative policies (with the stakeholders' α level of confidence and λ degree of pessimism towards risk) is given by Deng (1999) as follows

$$PI_i = \frac{S_i^+}{S_i^+ + S_i^-}, \quad i = 1, 2, \dots, 4. \quad (9.6)$$

Returning back to our case study, from Figure 9.12, we obtain the following performance matrix.

| | Criterion C ₁ | Criterion C ₂ | Criterion C ₃ |
|-----------------------------|--------------------------|--------------------------|--------------------------|
| Policy P₁ | (0.323, 0.459, 0.587) | (0.25,0.25,0.25) | (0.25,0.25,0.25) |
| Policy P₂ | (0.052, 0.075,0.126) | (0.25,0.25,0.25) | (0.25,0.25,0.25) |
| Policy P₃ | (0.106, 0.199, 0.307) | (0.25,0.25,0.25) | (0.25,0.25,0.25) |
| Policy P₄ | (0.186, 0.268, 0.394) | (0.25,0.25,0.25) | (0.25,0.25,0.25) |

Table 9.7: Performance Matrix for the Actual Case Study

The Deng performance index values for different values of α and λ in (0,1) are tabulated (and have been calculated using the procedures described previously) in Table 9.8

| | $\alpha = 0$ | $\alpha = 0.5$ | $\alpha = 1$ |
|---------------|---|---|---|
| $\lambda = 0$ | PI ₁ =0.618 PI ₂ = 0.382 PI ₃ = 0.420 PI ₄ = 0.489 | PI ₁ =0.649 PI ₂ = 0.35 PI ₃ = 0.423 PI ₄ = 0.493 | PI ₁ =0.678 PI ₂ = 0.322 PI ₃ = 0.433 PI ₄ = 0.501 |
| $\lambda = 1$ | PI ₁ =0.702 PI ₂ = 0.298 PI ₃ = 0.464 PI ₄ = 0.55 | PI ₁ =0.692 PI ₂ = 0.308 PI ₃ = 0.448 PI ₄ = 0.528 | PI ₁ =0.678 PI ₂ = 0.322 PI ₃ = 0.433 PI ₄ = 0.501 |

Table 9.8: Deng's Performance Indices

These results are depicted in Figure 9.16.

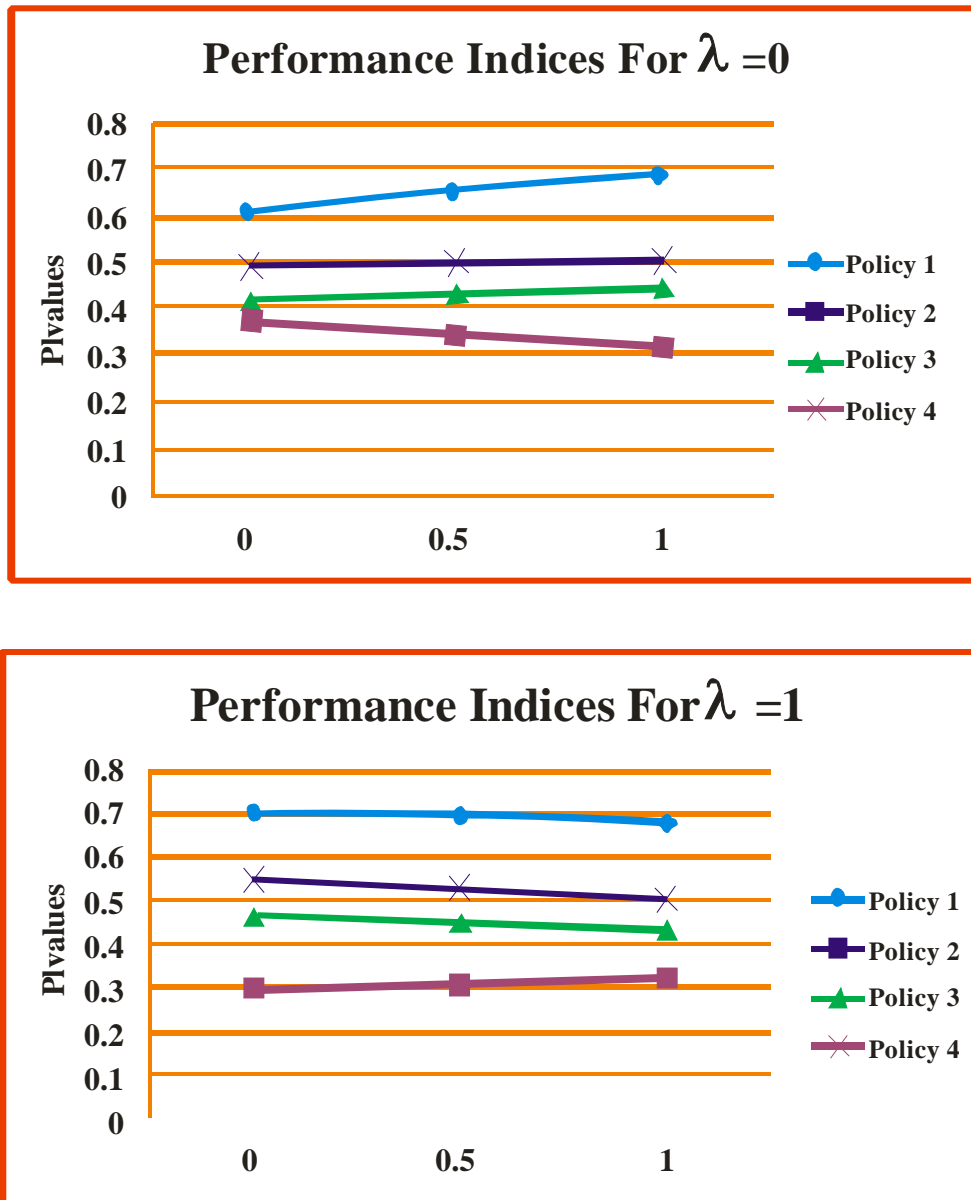


Figure 9.16: Graphical Sensitivity Analysis

From Figure 9.16, it can be discerned that, in an optimistic situation, the criteria show consistent and stable behaviour. Clearly, the policy P_1 has the highest performance index out of all the policies, and hence is the best among all the policies being considered. This in turn implies a high consensus among stakeholders perspectives regarding the considered policies and stability in the ranking of the policies (Hsu, 1999). By looking at the results of both the sensitivity analysis performed by the

functionality and that carried out using the graphical method, stakeholders might consider using a combination of policies to achieve the desired scenario. For instance, policies P_1 , P_2 and P_3 appear compatible with each other (Figure 9.16) in the sense that their impact on decision making is alike.

9.5. Evaluating the Impact of Executing the Chosen Policy

Fuzzy AHP study allows better reflection upon how the preference for the criteria and options may vary once stakeholders are informed of the impending policy implementation in the future year X . This exercise closely resembles the forward approach of the forward-backward method as it allows the stakeholders to see what future options may emerge in the context of the key environmental influences. In the present case study, as indicated by Deng's performance index, the policy P_1 , of providing financial incentives, is selected for implementation.

It is natural to presume that in the context of the implementation of the policy P_1 , the stakeholders' preferences for the criteria; sub-criteria and options will be different from the original pairwise comparisons shown in Figures 9.2 - 9.6. Here the original three criteria, viz. environmental, agricultural, technological, studied for selection of a suitable crop option are revisited with stakeholder preferences changed to illustrate the effect of preferred crop.

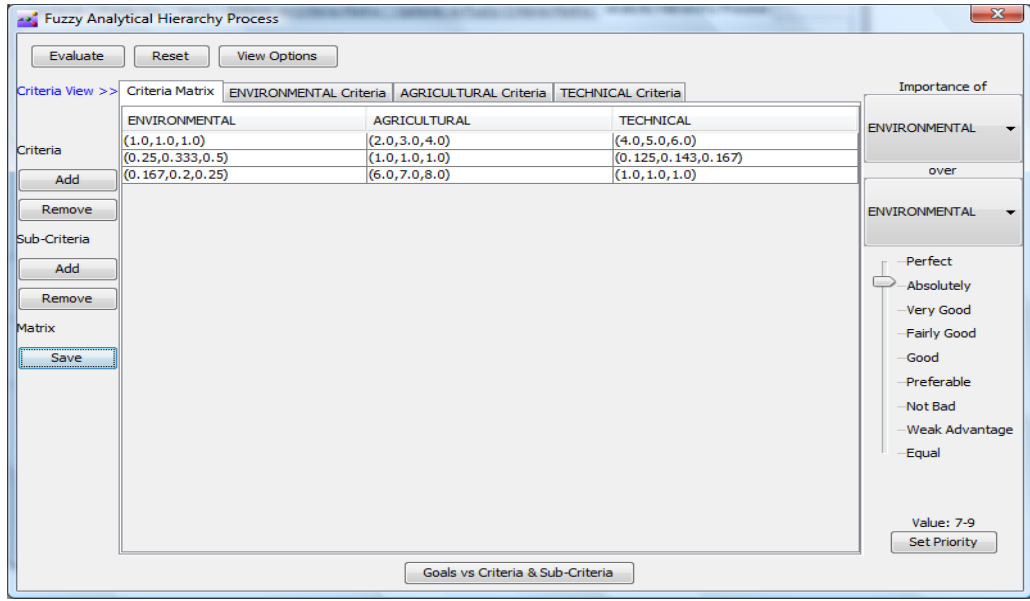


Figure 9.17: Pairwise comparison of criteria

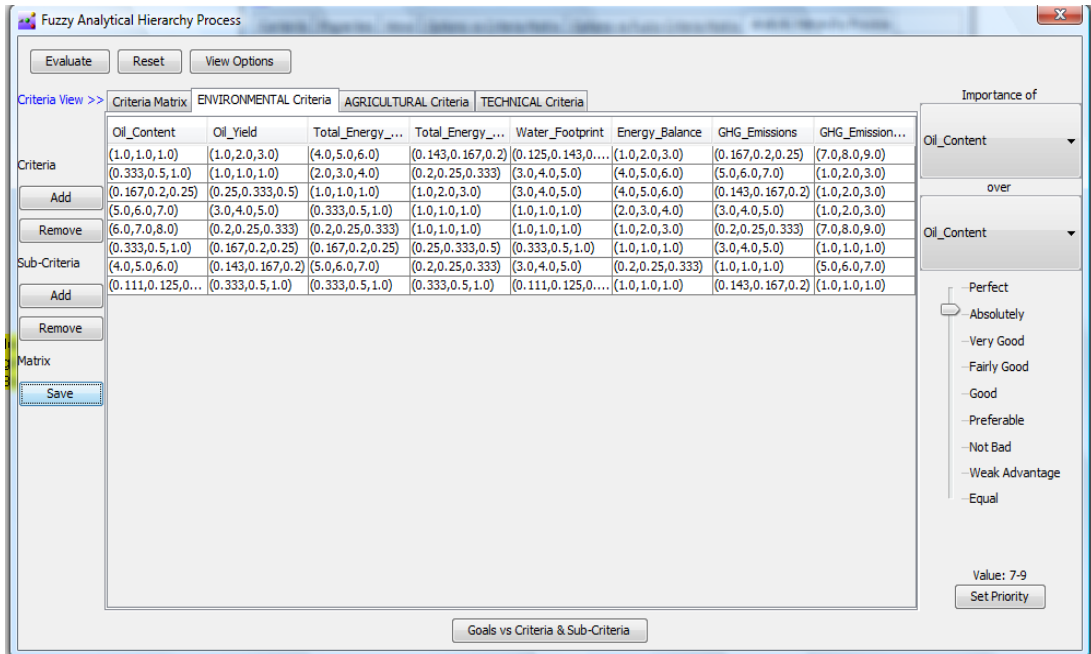


Figure 9.18: Pairwise Comparison of Sub-criteria

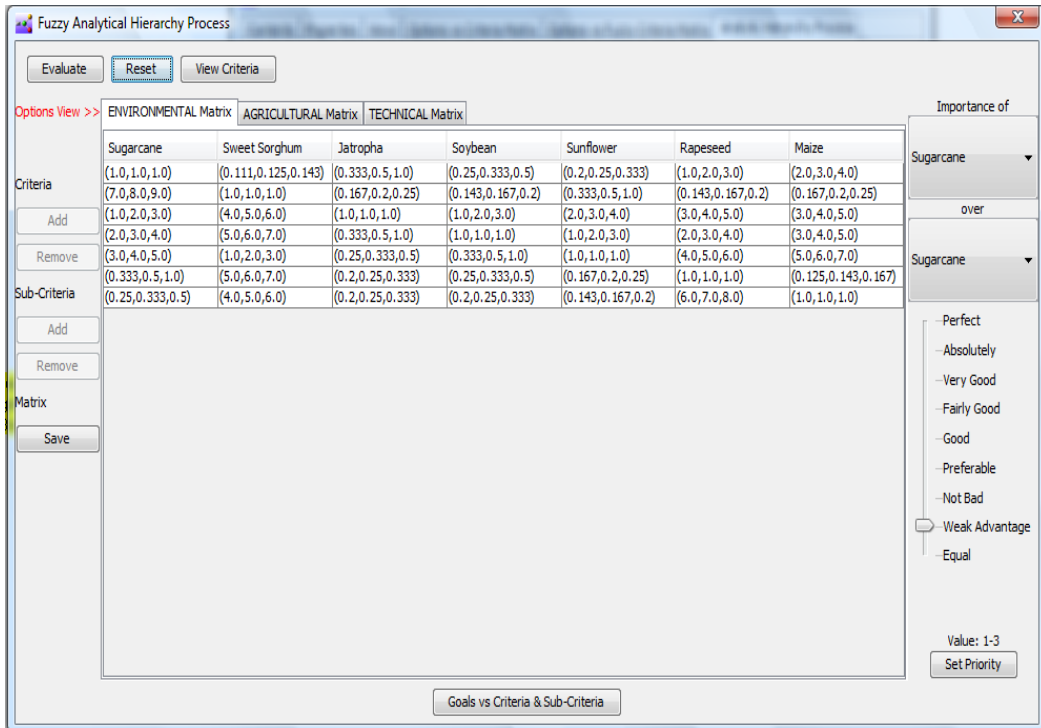


Figure 9.19: Pairwise Comparison of Options

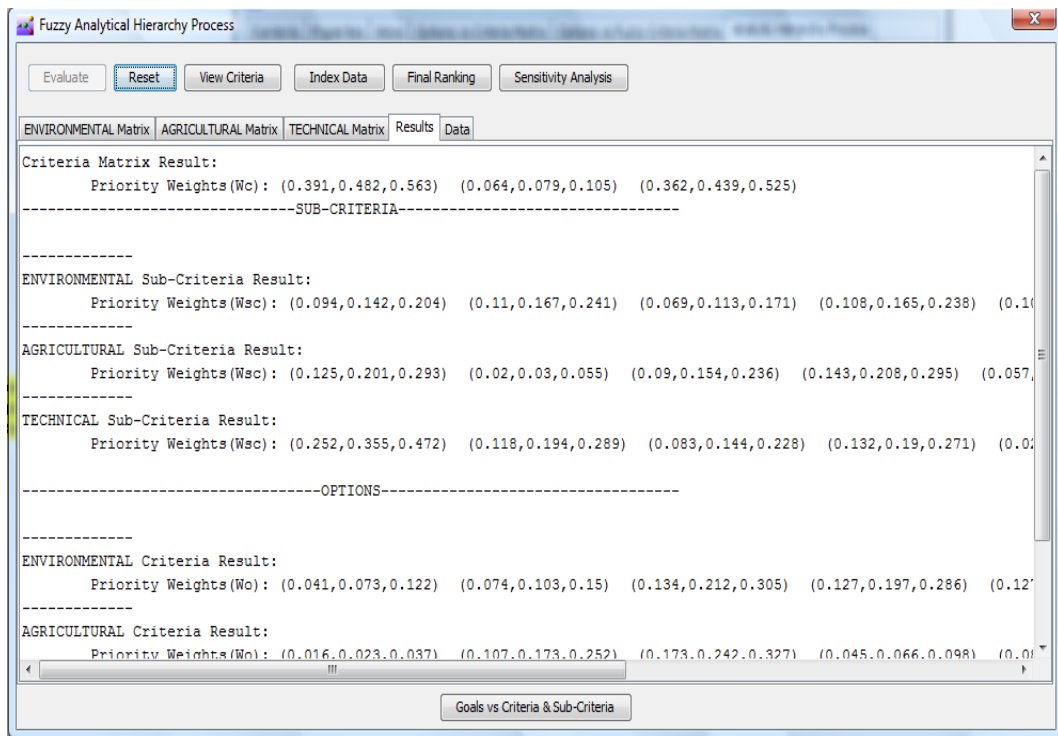


Figure 9.20: Priority Weights for Criteria-Sub-criteria In View of Policy P₁

The results of the analysis concluded that the prospect of implementing policy P_1 shifts the set of stakeholders' preferences (expressed in the pairwise comparisons) such that the final resulting preference has shifted in towards growing **jatropha** as a biofuel crop as opposed to sunflower.

9.6. Conclusions

By using AHP in conjunction with fuzzy set theory, qualitative judgment can be included effectively in the decision-making process and in making the comparison free from assessment bias (Mahmoodzadeh et al. 2007). This ability of fuzzy AHP, to incorporate uncertainty arising from subjective perception leads to a transparent decision making process which is consistent with uncertainties surrounding (most) of the parameters.

This Chapter has made use of fuzzy AHP to select the most suitable biofuel crop for cultivation in a particular region based on the fuzzy criteria, and also provided scope for performing scenario planning for the future. The fuzzy AHP functionality incorporated within the Compendium software facilitates the selection of sustainability options for the long term future.

Finally, it may be observed that by using fuzzy AHP, uncertainty and vagueness from subjective perception and the experiences of decision-maker can be effectively represented to reach to a more effective decision.

CHAPTER 10: RESULTS ANALYSIS, DISCUSSION AND CONCLUSIONS

Decision-making is a subjective process and there exists uncertainty even when highly technical knowledge is incorporated. This is especially true for sustainability-related policy design/decision making. According to Mitchell et al. (2004), sustainability asks us to step away from the role of the “objective decision maker” and enter the complex value laden realm of social priorities, social acceptability and participatory processes. This requires us to understand and account for the various uncertainties related to the decision making process and sustainability issues which go beyond statistical imprecision.

That alone informs the philosophical foundation of the present research. From an engineering perspective, the present study aim has been interpreted as designing a (software) system that allows for decision support which will enable both the selection of sustainable biofuels production related options (both in the immediate present and in the future) and policy design that will lead to the selection of sustainable options. Essentially the software system aims to provide decision-makers of diverse academic and professional backgrounds with a comprehensive system from which to launch in-depth investigations that are specific to unique scenarios.

This Chapter details the results, inferences and conclusions obtained from various case study models developed using different functionalities developed as a part of this research. The data in the case study models are taken for the Philippines (Chapters 5 & 6) and for the India (Chapters 7 to 9), and is presented in Appendix 1 and Appendix

2 respectively. However, the models and the functionalities developed herein are general and can directly be implemented to any other bio- geographical, agro-ecological, technical data.

10.1. Results and Discussion

The initial functionality developed herein, as an extension of the Compendium software, is the **Options vs Fuzzy Criteria Matrix**. This made use of fuzzy set theory as a means of allowing the incorporation of criteria whose values are best described using linguistic values. Using this functionality, the case study models, pertaining to land resource usage has been developed in Chapter 5 in which the evaluation of options has been undertaken with respect to both qualitative and quantitative criteria. The options of “**class B**” type of land has been identified through these models. This functionality has a further provision of performing a sensitivity analysis on the fuzzy criteria using linguistic variables. Such a sensitivity analysis has been performed on the fuzzy criteria, “Range of Growing Season” by varying its value from VERY LOW to VERY HIGH, after which, the option of land type, **class Y** has been recommended. This sensitivity analysis helped identify the criterion, the variation of whose value would impact the selection of options.

The aforementioned functionality provides support for obtaining solutions by identifying the satisfactory options and the fuzzy criterion influencing the recommendation of options.

The present study also demonstrated and implemented (Chapter 6) the concept of approaching degree described using a **fuzzy logic multi feature pattern recognition**

tool. The strength of the approach tested herein lies in integrating fuzzy logic in an important decision making process for identifying appropriate land for cultivation of crops. The approach is very flexible in the sense that it can be applied to situations where the exact data are not available and the information on land and crop is limited to vague subjective descriptions. In such circumstances, the model indicates that, in the Philippines, the PEZ of *cool highlands* and *warm lowlands* are most suited for cultivation of wheat and corn respectively.

However, Options vs Fuzzy Criteria Matrix and Multifeature Pattern Selection are not sufficient to provide support for recommending options and policies for the long term future. As a consequence, the Multi Criteria Decision Making (MCDM) technique of Analytical Hierarchy Process (AHP) and Fuzzy AHP was then incorporated within the Compendium software as a means of selecting sustainability options for the long-term future and providing a framework for formulating and testing the decision policies aimed at achieving sustainability.

The software functionalities of AHP and Fuzzy AHP allow for prioritizing the various criteria and their relevance to the designated goal. By establishing a single, long-term objective of providing a comprehensive model for sustainable biofuel production, policymakers can evaluate the impact that various strategies have on sustainability options pertaining to biofuels crops cultivation. For policymakers, the ability to evaluate such scenarios is ideal, because, based on varying circumstances, the adjustments to the sustainability policies might be necessary.

The case study models developed using the AHP functionality allowed for pinpointing a crop, namely **sugarcane** for biofuel production (Chapter 7). Seven crops were compared with respect to environmental, agricultural and economic criteria and their sub-criteria. This functionality allowed for the incorporation of both the stakeholder preferences and data related to these crops within the decision making process.

Using the same functionality, a further model has been developed that showed its efficacy in supporting policy decisions. Chapter 8 demonstrates how the AHP functionality can allow us to analyze the policies aimed at meeting a future goal related to environmental sustainability (inclusive of agricultural considerations). The AHP analysis was carried out to rank four plausible policies identified as a means of achieving the desired future goal. According to the AHP analysis of the policies, **policy P4** of providing financial incentives to farmers as farm subsidies and provision of easy credit is found to be the best out of all other policy options.

Finally, AHP has again been put to use as a tool for providing support for **scenario planning** by evaluating the plausible impact of implementation of policy P4 in the future. Hence, it can be seen that the Analytical Hierarchy Process functionality supports scenario planning and policy design by providing a venue for testing new decision policies by manipulating forces and potential responses to them in an experimental environment. The AHP functionality is now put to use as means of assessing the potential future scenarios rather than existing biofuel crops production schemes. This is achieved by means of a forward-backward planning mechanism. The revised model which focused on the agro-environmental sustainability as a founding

performance component identified **jatropha** as a suitable crop for sustainable biofuel cultivation. This can be confirmed by the means of sensitivity analysis.

As observed, the data collected for selection of a suitable crop are mostly fuzzy (lying between a range of values). For this reason, it has been decided to use a combination of the two concepts, namely the fuzzy set theory and MCDM (in the form of AHP) to extend the scope of existing AHP functionality by incorporating an extent analysis based Fuzzy AHP. The Fuzzy AHP functionality has been used to aid a decision making problem which revolves around suggesting the most suitable crop type for biofuel crops cultivation in India.

In Chapter 9, the case study based model developed using the Fuzzy AHP initially recommended **sunflower** as the ideal biofuel crop. Appropriate policies were explored and pinpointed as a means of encouraging the cultivation of the given crop.

Fuzzy AHP was then used for evaluating various policy scenarios to promote of the desired crop **Policy P₁** of providing financial incentives to farmers has been pinpointed ideal for encouraging the cultivation of non agricultural biofuels crop. This has also been validated by evaluating the policies using Deng's Performance Index method. Policy analysis has been carried out using Deng's Performance Index further as a means of testing the robustness of the Fuzzy AHP functionality. As an additional advantage, this study permitted the identification which policy combinations will be optimal in the context of the varying stakeholder attitude of regulations for land cover and usage has been pinpointed as an ideal policy for encouraging the cultivation of biofuels crops of land other than the arable land. This has also been validated by

evaluating the policies using Deng's Performance Index method. Policy analysis has been carried out using Deng's Performance Index further as a means of testing the robustness of the Fuzzy AHP functionality. As an additional advantage, this study identified which policy combinations are likely to be optimal in the context of the varying stakeholder attitude.

Hence in conclusion, fuzzy Analytical Hierarchy Process functionality can be used not only to recommend satisfactory options but also to provide a framework for formulating and testing decision policies geared at achieving a particular future goal or scenario.

10.2. Contributions of the Research

The research has fulfilled its objective of designing a system to support policy design for sustainable biofuel production by extending the functionality of the benchmark software Compendium. This has been done by the incorporation of the following functionalities which allow for the integration of objective measurements with value judgements in the decision making process:

- **Options vs Fuzzy Criteria Matrix:** Allows for the inclusion of qualitative criteria (by the use of fuzzy logic) along with quantitative criteria as a means of finding robust solutions to the issues being dealt with. Integration of sensitivity analysis allows the users to calculate the potential impact a variety of occurrences (expressed in terms of linguistic variables) may have on the recommendation of the options.
- **Analytical Hierarchy Process:** Allows for combining factual data and stakeholder preferences (in form of pairwise comparisons) to recommend

possible options and policies which may help achieve the desired future sustainability goal. The users can further play out the possibilities of the given decision policies and examine their long term effects. Through the provision of sensitivity analysis, the impact of varying stakeholder preferences (represented in terms of variation in criteria weights) can be assessed on the selection of options.

- **Fuzzy Analytical Hierarchy Process:** Combines the distinct features of both AHP and fuzzy logic to allow for estimate preference comparisons for the criteria and alternatives in terms of linguistic variables. Like the AHP functionality, fuzzy AHP provides support for assessing the possibilities of the given decision policies and examining their long term effects.

The present software has been designed not only to provide insight not only into the performance of each of the sustainability options within the current regional constraints and but also to help identify sustainability options and formulate policies over a pre-established time-frame. However, the greatest benefit of the software stems from the fact that it can be used by decision-makers coming from a variety of backgrounds and who do not possess either programming skills or in depth knowledge of the concepts of fuzzy logic and MCDM utilized for software development.

10.3. Scope of Future Improvement in the Research

Development of a software model based on fuzzy logic multifeature pattern recognition (described in Chapter 6) would be a natural enhancement of the present research. A standalone model could be created using Matlab (which allows for high

level mathematical programming). It is strongly recommended that future research be conducted using data from field study based surveys. It is expected that by doing so; socio economic criteria can find a better representation in the decision support models. In order to access information about the biofuel production systems in terms of relevant data and practices possibility of enhancing the current work with the use of Geographical Information Systems (GIS) should be explored. A GIS system provides the basis of different physical environmental criteria such as energy output/input ratio, environmental costs and design of different alternatives on a crop wise basis (Tiwari et al. 1999). Availability of in depth GIS data pertinent to land attributes could enable the identification of the possible changes that may take place in net primary productivity, carbon sources and sinks and biodiversity related concerns (Turner et al. 2007). These in turn can allow for the inclusion of a greater number of criteria and options within the decision making process. Finally, a commodity chain analysis/life cycle analysis may be carried out to allow better qualitative and quantitative insights into the sustainability related issues pertaining to biofuel production by increasing the scope of decision parameters that one may consider. Life cycle analysis enables this by helping us quantify the environmental impacts of a given system (from cradle to grave) and express environmental performance in terms of quantified environmental impact categories (Mitchell et al. 2004). The standard commodity chain analysis can be further enhanced by inclusion of biomass monitoring and landscape-scale analysis of a given region with significant pressure from agriculture commodity production (Morel and Morel, 2009).

10.4. Conclusions

The present research recognises the inherent sustainability challenges in biofuels production and provides a software tool which allows for the incorporation of the stakeholders' preferences and relevant data in order to provide the decision support for policy formulation. The concepts of fuzzy logic, Analytical Hierarchy Process and a combination of the two, i.e. Fuzzy AHP have been utilized in developing the software functionalities.

According to Belton and Stewart, (2002), “through organization, synthesis and appropriate presentation of information, policy makers can be guided into identifying a preferred course of action and achieve a more satisfying option”. Ultimately, the relationship between situational analysis and policymaker decisions is founded on unique scenarios and diverse variables, an analytical capability that this software system endeavours to provide. The social, economic, and environmental parameters pertaining to biofuels production can be incorporated within the framework of the software to aid the development of different sustainability models and relevant policies, making the utility of software easily transferable across a wide range of geographic regions, and diverse stakeholder viewpoints.

This research addresses a deficit in the field of sustainable biofuel research, highlighting the benefits of a more comprehensive policy oriented system. Policy research is needed to identify approaches and policy tools that would encourage the sustainable production of biofuels in the long term. The software system aimed at providing support for policy design comes is timely given that there will be a long term requirement of sustainable biofuels industry, demanding a sustained and

adaptive policy commitment that is best based on identification and analysis of the opportunities, risks and trade-offs, and adjusting policies as required (Bekunda, 2008).

By involving field studies and experts' knowledge in the above case studies a more comprehensive and concrete analysis of the cases both in the crisp and the fuzzy scenarios can be obtained. Therefore, while uncertainty is unavoidable in the design of comprehensive sustainable biofuels production policies, this form of decision support will allow policy makers to confirm the appropriateness of their initiatives.

From both a knowledge and ethical contexts, the software system developed as a part of this research contributes to the larger goal of sustainability. The interactions of fundamental physical, chemical and biological processes have given rise to the unique diversity, complexity, and tenacity of Planet Earth and its inhabitants. Acute or protracted environmental change, whether global or local, natural or anthropogenic, present a grand challenge to scientists and engineers and necessitate a coordinated, multi-disciplinary effort to identify and understand these changes and help define our role in the stewardship of planet Earth. The present research has been undertaken with this in mind.

REFERENCES

- Abaza, H and Baranzini, A, (2002), "Implementing Sustainable Development", Integrated Assessment and Participatory Decision Making Process". UNEP and Edward Elgar, Cheltenham (UK) and Northampton, Ma (USA).
- Abildtrup, J., Audsley, E., Fekete-Farkas, M., Giupponi, C., Gylling, M., Rosato, P., Rounsevell, M., (2006), "Socio-economic scenario development for the assessment of climate change impacts on agricultural land use: a pairwise comparison approach", *Environmental Science and Policy* 9, 101-115.
- ADB (2007), "Adopting integrative thinking to change perspectives and decision making processes" <http://www.adb.org/Documents/Papers/Resource-Efficient-Economies/Chapter-III.pdf> [link last accessed on 02/07/2010].
- Anagnostopoulos, K. P., Gratziou, M., and Vavatsikos,(2007), " Using fuzzy analytical hierarchy process for selecting wastewater facilities at prefecture level", *European Water* 19/20.
- Alphonse, C.B., (1997), "Application of analytical hierarchy process in agriculture in developing countries", *Agricultural Systems* 53, 97-112.
- Antunes, C.H. and Oliveira, C. (2004), "A multiple objective model to deal with economy–energy–environment interactions", *European Journal of Operations Research*, Volume 153, Issue 2, 370-385.
- Arsalan, T., (2009), "A hybrid model of fuzzy and AHP for handling public assessments on transportation projects", *Transportation* 36, 97-112.
- Bekunda, M., Palm, C. A., Fraiture, C. and Leadley, P.(2008), "Biofuels in Developing Countries ", Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment, Gummerts Bach, Germany, Sept 22-25.
- Bereierova, L. and Choudhari, M. (2001), "An Introduction to Sensitivity Analysis", Prepared for the MIT System Dynamics in Education Project <http://sysdyn.clexchange.org/sdep/Roadmaps/RM8/D-4526-2.pdf> [link last accessed on 02/07/2010].

Belton V. and Stewart T. J.(2002), “Multiple Criteria Decision Analysis: An Integrated Approach”.
Published by Springer, ISBN 9780792375050.

Bishop, I.D., Stock, C. and Williams, K.J., (2009), “Using virtual environments and agent models in multi-criteria decision-making”, *Land Use Policy*, Volume 26, Issue 1, 87-94.

Boddiger, D. (2007), “Boosting biofuel crops could threaten food security” *The Lancet*, Volume 370, Issue 9591, 923 - 924,

Bohensky, E., Reyers, B. and van Jarsveld, A. S.,(2006) “ Future Ecosystem Services in a Southern African Basin: a Scenario Planning Approach to Uncertainty”, *Conservation Biology* 20 (4), 1051-1061.

Boulanger, P. M. and Brechet, T., (2005), “Models for policy making in sustainable development: The state of art and perspectives of research”, *Ecological Economics*, 337-350.

Buckley, J. J. (1985), “Fuzzy hierarchical analysis”, *Fuzzy Sets and Systems*17, 233-247

Browne, D., O’ Regan, B., Moles, R. (2009), “Use of multi-criteria decision analysis to explore alternative domestic energy and electricity policy scenarios in an Irish city-region”, *Energy*, Volume 35, Issue 2, 518-528.

Cavallaro, F. and Ciraolo, L. (2005), “ A multicriteria approach to evaluate wind energy plants on an Italian island”, *Energy Policy*, Volume 33, Issue 2, 235-344.

Cassman, K.G., (2007), “Climate change, biofuels and global food security”, *Environ. Res. Letters* 2, 215-223.

Chang, D. Y., (1996), “Applications of the extent analysis on fuzzy AHP”, *European Journal of Operation Research* 95, 649-655.

Chee Tahir, A. (2006), “Measuring the sustainability of a palm oil business using sustainability metrics”, *DPhil Thesis*, Oxford.

Chermack, T. J., (2003), "Improving decision making with scenario planning", *Futures* 36 (3), 295-309.

Chiou, H.K. and Tzeng, G.H. (2002), "Fuzzy Multiple-Criteria Decision-Making Approach for Industrial Green Engineering", *Environmental Management*, Volume 30, Issue 6, 0816-0830

Chu, T.C. and Lin, Y., (2009), "An extension to fuzzy MCDM", *Computers and Mathematics with Applications*, Volume 57, Issue 3, 445-454

Compendium Institute, <http://www.compendiuminstitute.org> [link last accessed 22/10/08].

Conklin, J. (2006), "Dialogue Mapping: Building Shared Understanding of Wicked Problems", John Wiley and Sons Ltd., ISBN: 978-0-470-01768-5.

Cornelissen, A.M.G., van den Berg, J., Koops, W.J., Grossman, M., Udo, H.M.J. (2001), "Assessment of the contribution of sustainability indicators to sustainable development: a novel approach using fuzzy set theory", *Agriculture, Ecosystems and Environment*, Volume 86, Issue 2, 173-185

Darton, R. C., (2003), "Scenarios and metrics as a guide to a sustainable future: The case of energy supply", *Trans IChemE* 81, Part B, 295-302

Deacon, J. (2005), "Object oriented analysis and design : a pragmatic approach", ISBN-10: 0321263170

Demirbas, A. (2008), "Biofuels sources, biofuel policy, biofuel economy, and global biofuel projections", *Energy Conversion and Management* 49, 2106-2116.

Demirel, T., Mudal, H., Demirel, N. C. and Yucenur, G. N.(2009), "Multi Criteria Evaluation of Land Cover Policies using fuzzy AHP and fuzzy ANP: The case of Turkey", *Human and Ecological Risk Assessment: An International Journal*, 15:4, 746-764

De Montis A, De Toro P., Droste -Franke B., Omann, I., Stagl., S. (2000) "Criteria for quality assessment of MCDA methods" *Proc. 3rd Bienn. Conf. Eur. Soc. Ecol. Econ.* Vienna. May 3-6, 2000.

- Deng, H.(1999), “Multi criteria analysis with fuzzy pairwise comparisons”, *International Journal of Approximate Reasoning* 21, 215-231.
- DeSanctis, G and Gallupe, R.B. (1987), “A foundation for the study of group decision support systems”, *Management Science* 33, No.5, 589-605
- Dinh, L. T. T., Guo, Y., Mannan, M.S., (2009), “Sustainability evaluation of biodiesel production using multi Criteria decision making”, *Environmental Progress and Sustainable Energy (Special Issue: Sustainable Energy)* 28, 38-46.
- Doornbosch, R. and Steenbilk, R., (2008), “Biofuels: Is the cure worse than the disease?”, *Round Table on Sustainable Development*
- Duinker, P.N. and Greig, L.A. (2006), “Scenario analysis in environmental impact assessment: Improving explorations of the future”, *Environmental Impact Assessment Review*, Volume 27, Issue 3, 206-219
- Dyer, R. F. and Forman, E. H., (1992) “Group decision support with the analytic hierarchy process”, *Decision Support Systems* 8, 99-124.
- Elghali, L., Clift, R., Sinclair, P., Panoutsou, C. and Bauen, A., (2007), “Developing a sustainability framework for the assessment of bioenergy systems”, *Energy Policy*, Volume 35, Issue 12, 6075-6083.
- Entani and Tanaka, (2005), “Interval estimations in AHP by linear programming in Liu” *Fuzzy Logic, Soft Computing and Computational Intelligence*.
- European Commission (2008), “Biofuel Sustainability in the European Policy”, *European Biofuel Technology Platform (31st January, 2008)*, European Commission.
- Fahey, L. and Randall, R.M. (1998), “Learning from the future: Competitive foresight scenarios”, ISBN-10: 0471303526
- Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P. (2008), ‘Land Clearing and the Biofuel Carbon Debt.’ *Science* 319, No. 5867, 1235-1238.

FAO Statistics(2001), “The Philippines” Gateway to Land and Water Information http://www.fao.org/ag/agl/swlwpnr/reports/y_ta/z_ph/ph.htm#use,2004, YieldData:<http://www.fao.org/docrep/t4470e/t4470e05.htm> [links last accessed on 23/12/08]

FAO (2008),“http://www.fao.org/nr/water/docs/wwf5/b_adg_panel_wfen/Water-biofuels-Figures-Jippe-May-2008.ppt”[link last accessed on 02/01/2010].

FAO (2010), “Crop Water Information: Wheat”, <http://www.fao.org/nr/water/cropinfo_wheat.html>

Figueira, J., Greco, S. and Ehrgott, M.,(2005), ” Multiple criteria decision analysis: state of the art surveys”, 57, ISBN 038723067X, 9780387230672.

Fischer, G., Prieler, S., van Velthuisen, H., Berndes, G., Faaij, A., Londo, M., de Wit, M. (2009), “Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land use scenarios” Biomass and Bioenergy, Volume 34, Issue 2, 173-187.

Fraiture, C., Giordano, M., Liao, Y. (2007), “Biofuels and implications for agricultural water use: blue impacts of green energy”, Water Policy 10 Supplement 1 (2008) 67–81

Foreman and Gass (1998), “ Analytical Hierarchy Process “, University of Washington

Gagliardi, F., Roscia, M., and Lazariou, G.(2007), “Evaluation of sustainability of a city through fuzzy logic”, Energy, Vol 32, 795-802.

Gerbens-Leenes, W. Hoekstra, A. Y. and van der Meer, T. H. (2008) The water footprints of bioenergy. Available at: www.pnas.org/cgi/doi/10.1073/pnas.0812619106 (Accessed on 21/12/2009)

Gomez-Limon, J. A., Arriaza, M. and Riesgo, L.(2003), “An MCDM Analysis of Agricultural Risk Aversion” European Journal of Operational Research, Vol. 151, pp. 569.

Gonsalves, J. B. (2006) As assessment of biofuels industry in India. Report for UNCTAD Available at: <http://www.biotechnologie.de/BIO/Redaktion/PDF/de/laenderfokus/indien-biofuel-unctad.property=pdf,bereich=bio,sprache=de,rwb=true.pdf> (Accessed on 21/12/2009).

- Groom, M.J., Gray, E.M., Townsend, P.A. (2007), "Biofuels and Biodiversity: Principles for Creating Better Policies for Biofuel Production", *Conservation Biology*, Volume 23, Issue 2, 602-609.
- Gumus, A. T.(2009.), "Evaluation of hazardous waste transportation firms by using a two step fuzzy-AHP and TOPSIS Methodology", *Expert Systems with Applications* 36, 4067-4074.
- Hill, J., Nelson, E., Tilman, D., Polasky, S., Tiffany, D. (2006), "Environmental, Economic, and Energetic Costs and Benefits of Biodiesel and Ethanol Biofuels." *PNAS* 103, No. 30, 11206-11210.
- Hsu, T. H.(1999), "Public Transport System Project Evaluation Using the Analytic Hierarchy Process: A Fuzzy Delphi Approach", *Transportation Planning and Technology* 22:4, 229-246.
- Hung, K. C., Yang, G.K., Chu, P., Jin, W.T.H. (2008)"An enhanced method and its application for fuzzy multi-criteria decision making based on vague sets", *Computer-Aided Design*, 40, 447-454
- IPCC, (2006), "N₂O Emissions from Managed Soils, and CO₂ Emissions from Lime and Urea Application" Intergovernmental Panel on Climate Change.
- Iyer, K.C, and Sagheer, M., "Risk and Uncertainty Assessment in PPP Infrastructure Projects: need for a System Dynamics Framework", http://www.indianjournals.com/glogift2k6/glogift2k6-1-1/theme_5/Article%2011.htm (link last accessed on 16/02/09).
- Kahraman, C., Cebeci, U., Ruan, D.(2004), "Multi attribute comparison of catering service companies using fuzzy AHP: the case of Turkey", *International Journal of Production Economics* 87, 171-184.
- Kangas, J., Kangas, A., Leskinen, P., and Pykalainen, J.(2001), "MCDM Methods in Strategic Planning of Forestry on State Owned Lands in Finland: Applications and Experiences", *Journal of Multi Criteria Decision Analysis*, 10, 257-271.
- Kaufmann, A. and Gupta, M. M.(1991), "Introduction to Fuzzy Arithmetic", van Nostrand Reinhold Company, ISBN 044-2008-996.

Keleman, A. and Rano, H.G. (2008), "Biofuels and Rising Food Prices: Mexico's 2007 Tortilla Crisis", Presentations from the Food Security and Environmental Change Conference, Oxford, 2-4 April 2008 http://www.gecafs.org/documents/PP12Keleman_000.pdf [link last accessed on 02/07/2010]

Klir, G. J. and Ayyub, B. M. (2006), "Uncertainty modelling and analysis in engineering and the sciences" ISBN 1584886447, 9781584886440, CRC Press.

Koh, L.P. and Ghazoul, J. (2008), "Biofuels, Biodiversity, and people: Understanding conflicts and finding opportunities", *Biological Conservation*, 141, (10) 2450-2460.

Kok, K. (2009), "The potential of fuzzy cognitive maps for semi-quantitative scenario development, with an example from Brazil", *Global Environmental Change*, 19, 122-133.

Kwong, C.K. and Bai, H. (2002), "A fuzzy AHP approach to the determination of importance of weight of customer requirements in quality function deployment", *Journal of Intelligent Manufacturing* 13:5, 367-377.

Larson, B.A. (2007), "Sustainable Development Research Advances", Nova Publishers, ISBN 1600218466, 9781600218460.

Land Resources Information Systems in Asia (2000), Proceedings of Regional Workshop, Quezon City, Philippines, 25-27 January.

Laukkanen S, Kangas A, Kangas J (2002), "Applying Voting Theory in Natural Resource Management: a case of multi-criteria group decision support" *Journal of Environmental Management*, 64, 127-137.

Liang, G. S. (1999), "Fuzzy MCDM Based on Ideal and Anti-Ideal Concepts", *European Journal of Operational Research*, Vol. 112, pp. 682-691.

Liu, K. F. R (2007), "Evaluating environmental sustainability: An integration of multi criteria decision making and fuzzy logic", *Environment Management*, 39, 721-736,

- Loken, E. (2007), "Use of multicriteria decision analysis methods for energy planning problems", *Renewable and Sustainable Energy Reviews*, Volume 11, Issue 7, 1584-1595
- Mahmoodzadeh, S., Shahrabi, J., Pariazar, M., Zaeri, M.S. (2007), "Project selection by using fuzzy AHP and TOPSIS technology", *International Journal of Humanities and Social Sciences*, Volume 1, No.3.
- Martinsen, D. and Krey, V. (2008), "Compromises in energy policy - using fuzzy optimization in an energy systems model", *Energy Policy*, 36, 2983-2994.
- Malczewski, J. (1999), "GIS and multi-criteria decision analysis", ISBN 0-471-32944-4
- Malhi, Y., Betts, R.A., Roberts, J.T., (2008), "The future of the Amazon: new perspectives from climate, ecosystem and social sciences", *Phil. Trans. R. Soc.*, 1729-1735
- McBratney, A. B. and Odeh, I. O. A. (1997), "Applications of fuzzy sets in soil science: fuzzy logic, fuzzy measurements and fuzzy decisions", *Geoderma* 77, 85-117.
- Meade, L. and Sarkis, J., (1998), "Strategic analysis of logistics and supply chain management systems using analytic network policy", *Transportation Research Part E: Logistics and Transport Review*, 34 (3), 201-215.
- Mei, X., Rosso, R., Huang, G.L., Nie, G.S.,(1989), "Application of analytical hierarchy process to water resource and management in Beijing, China", *Closing the Gap Between Theory and Practise, Proceedings of the Baltimore Symposium, IAHS Publication no. 180.*
- Mendoza, G. A. and Prabhu, R, (2003), "Fuzzy Methods for assessing criteria and indicators of sustainable forest management", *Ecological Indicators*, 3 (4), 227-236.
- Mitchell, C. A., Carew, A.L. and Clift, R. (2004), "The Role of Professional Engineer and Scientist in Sustainable Development" in *Sustainable Development in Practise: Case Studies for Engineers and Scientists* ISBN: 0-470-85609-2
- Mol, A.P.J.,(2007), "Boundless biofuels? Between environmental sustainability and vulnerability", *Sociologia Ruralis* 47, 297-315.
- Molden, D., Frenken, K., Barker, R. & de Fraiture, C. (2007a). Trends in water and agricultural development. In: *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*, Chapter 2, Earthscan, London and International Water Management Institute, Colombo

- Morel, A.C. and Morel, B. (2009), "How Could Carbon Credits for Reducing Deforestation Compete with Returns from Palm Oil: A Proposal for a More Flexible REDD Valuation Tool". Journal of Sustainable Forestry. In press
- Musters, C.J.M., de Graaf, ter Keurs, W.J., "Defining socio-environmental systems for sustainable development", Ecological Economics, Volume 26, Issue 3, 248-253.
- Nasibov, E. N. and Mert, A.(2007), "On methods of defuzzification of parametrically represented fuzzy numbers", Automatic Control and Computer Sciences 51, 265-273.
- Openshaw, K. (2000), "A review of *Jatropha curcas*: an oil plant of unfulfilled promise", Biomass and Bioenergy, Volume 19, Issue 1, 1-15
- Pan, N. F.(2008), "Fuzzy AHP approach for selecting the suitable bridge construction method", Automation in Construction 17, 958-965.
- Papalexandrou, M.A., Pilavachi, P.A., Chatzimouratidis, A.I. (2008), "Evaluation of liquid biofuels using the Analytical Hierarchy Process", Process Safety and Environment Protection 86, 360-374.
- Percin, S.,(2008), "Use of fuzzy AHP for evaluating the benefits of information sharing decisions in a supply chain", Journal of Enterprise Information Management, 21(3), 263-284.
- Peterson, G.D., Cumming, G.S., Carpenter, S.R. (2003), "Scenario Planning: a Tool for Conservation in an Uncertain World", Conservation Biology, Volume 17, Issue 2, 358-366.
- Peters and Thielman (2008), " Promoting Biofuels: Implications for developing countries" , Energy Policy, Volume 36, 4, 1538-1544
- Phalan, B.(2009), "The social and environmental impacts of biofuels in Asia: an overview", Applied Energy, doi: 10.1016/j.apenergy.2009.04.046.
- Po, K. L. and Ang, V. W.(1999), "Transportation fuels and policy for Singapore: an AHP planning approach", Computers and Industrial Engineering 37, 507-525.
- Pohekar, S.D. and Ramachandran, M, (2004), "Application of multi criteria decision making to sustainable energy planning- A review", Renewable and Sustainable Energy Reviews 8, 4, 365-381.

- Phillis and L. Andriantiatsaholainaina (2001), "Sustainability: an ill-defined concept and its assessment using fuzzy logic", *Ecological Economics* (37), 435–456.
- Phdungslip, A., (2009), "Integrated energy and carbon modelling with a decision support system: Policy scenarios for low-carbon city development in Bangkok", *Energy Policy*
- Prakash, T. N.(2003), "Land suitability analysis for agricultural crops: a fuzzy multi criteria decision making approach", *International Institute of Geo-information Science and Earth Observation*.
- Pramanik, S. and Roy, T. K. (2007), "Fuzzy goal programming approach to multilevel programming problems," *European Journal of Operational Research*, 176, 1151-1166.
- Rahman, S.H., Ahmed, A.M., Bauer, A., Bhushan, I., Carrasco, B., Chatterjee, S., Dawson, R.L.T., Fawcett, B., Hussain, A., James, W.E., Kannan, K., Lin, T., Mitra, S., Olega, A., Renfro, R.Z.H., Roche, F.C., Shrestha, S., Siddiq, A., Srinivasan, R., Zahid, S.N., Zhuang, J., Zhukov, E.G., Alamgir, M., (2008), "Soaring Food Prices: Response to the Crisis". Asian Development Bank, Manila, Philippines. <<http://www.adb.org/Documents/Papers/soaring-food-prices/soaring-food-prices.pdf>>.
- Ramanathan, R and Ganesh L. S.,(1995), " Energy Resource Allocation using Qualitative and Quantitative Criteria: An Integrated Model Using Goal Programming and AHP", *Socio-Economic Planning Science*, 29 (3), 197-218.
- RoundTable on Sustainable Biofuels (2008), "Global Principles and Criteria for Sustainable Biofuels Production" (École Polytechnique Fédérale de Lausanne Energy Center, Lausanne, Switzerland).
- Robertson GP, et al. (2008) Agriculture sustainable biofuels redux. *Science* 322:49–50.
- Ross, T. (2005), "Fuzzy Logic with Engineering Applications", John Wiley and Sons, ISBN: 0-470-86075-8
- Saaty, T.L., (1980), "The analytic hierarchy process: planning, priority setting, resource allocation", McGraw Hill.
- Saaty, T.L. and Gholamnezhad, H. (1982), "High-level nuclear waste management: analysis of options", *Environment and Planning B*, 181-196

Saaty, T.L. and Vargas, L.G. (2001), “Models, methods, concepts, and applications of the analytic hierarchy process”, ISBN 0792372670, 9780792372677.

Saaty, T.L. (2005), “Theory and Applications of the Analytic Network Process: Decision Making with Benefits, Opportunities, Costs and Risks”, ISBN 1-888603-06-2.

Scharlemann, J., (2008),“Environmental Science: how green are biofuels?” *Science* 4, 319. 43 – 44, DOI: 10.1126/science.1153103.

Schmoltdt, D.L., Jones, H., Oliver, I. (2007), “Expert panel assessment of attributes for natural variability benchmarks for biodiversity”, *Austral Ecology*, 32, 453-475

Selvin, A.M., Buckingham, S., Conklin, J. (2001), “Compendium: Making Meetings into Knowledge Events”, Austin TX, 4-7 March.

Sheppard, S.R.J. and Meitner, M.J. (2005), “ Using multi-criteria analysis and visualisation for sustainable forest management planning with stakeholder groups”, *Forest Ecology and Management* 207 (2005), 171–187.

Shum, S. B., Selvin, A. M., Sierhuis, M., Conklin, J., Haley, C. B. and Nuseibeh, B. (2006), “Hypermedia support for argumentation-based rationale: 15 Years on from gIBIS and QOC”, *Rationale Management in Software Engineering*, Springer-Verlag, London, 111-132.

Skrzypczak, S (2007). “Extension of Compendium to manage an option vs criteria matrix decision support”, MSc dissertation, Oxford Brookes University (Dr. Arantza Aldea and Dr. René Bañares-Alcántara, co-supervisors)

Sorensen, C. G., Madsen, N. A., Jacobsen, B. H., (2005), “Organic Farming Scenarios: Operational Analysis and Cost of Implementing Innovative Technologies”, *Bio systems Engineering* 91(2), 127-137

Sun Microsystems (2002), “ Designing Enterprise Applications with J2EE Platform, Second Edition”<<http://www.google.co.uk/imgres?imgurl=http://java.sun.com/blueprints/guidelines/designing>

_enterprise_applications_2e/images/app-archa2.gif&imgrefurl=http://java.sun.com/blueprints/guidelines/designing_enterprise_applications_2e/app-arch/app-arch2.html&h=361&w=516&sz=35&tbnid=k2MfKT62eiPJZM:&tbnh=92&tbnw=131&prev=/images%3Fq%3Dmodel%2Bview%2Bcontroller&zoom=1&q=model+view+controller&hl=en&usg=__6KsKfRQT9vA_XCaZ2DtRYtkjA4A=&sa=X&ei=Y1KDTMmJMd3NjAfkp_yPCA&ved=0CC4Q9QEwAw

> Link last accessed on 02/09/2010

Sun Microsystems (2005), “Java Programming Language SL-275”

Sperling, D. and Gordon, D. (2009), “Brazilian Cane Ethanol: A Policy Model”, in *Two billion cars: driving toward sustainability*. Oxford University Press, New York. 95–96. ISBN 9780195376647.

Srdjevic and Medeiros, (2008), “Fuzzy AHP assessment of water management plans”, *Water Resource Management* 22, 877-894.

Teknomo, K. (2008), “Analytic hierarchy process (AHP) Tutorial” .
<http://people.revoledu.com/kardi/tutorial/ahp/> [link last accessed on 02/03/09].

Tenerelli P and Monteleone, M. A.(2008), “A combined land crop multi criteria evaluation for agro-energy planning”, Italy: SUSTSOIL, University of Foggia.

Tirado, F. F. and Lopez, C. (2008), “Prioritizing objectives to evaluate environmental, economic and social impacts of biofuel in Spain”, 12th Congress of European Association of Agricultural Economists.

Tiwari, D. N., Loof, R., Paudyal, G. N.(1999), “Environmental-economic decision making in Lowland agriculture using multi criteria analysis techniques”, *Agricultural Systems* 60, 2, 99-112.

Tran, L. T., Knight, G., O’ Neill, R., Smith, E. R., Riitters, K. H. and Wickham, J., (2002), “Fuzzy Decision Analysis for Integrated Environmental Vulnerability Assessment of the Mid-Atlantic Region”, *Environmental Management*, Volume 29(6).

Tsuar, H. S. and Wang, C. H. (2007), “The Evaluation of Sustainable Tourism Development by Analytic Hierarchy Process and Fuzzy Set Theory: An Empirical Study on the Green Island in Taiwan”, *Asia Pacific Journal of Tourism Research*, Volume 12(2), 127-145

Torbert, H.A., Krueger, E., Kurtener, D., Potter, K.N. (2009), "Evaluation of Tillage Systems for Grain Sorghum and Wheat Yields and Total Nitrogen Uptake in the Texas Blackland Prairie", *Journal of Sustainable Agriculture*, Volume 33, Issue 1 ,96 – 106

Turner, R.K., Burgess, D., Hadley, D., Coombes, E., Jackson, N. (2007), "A cost–benefit appraisal of coastal managed realignment policy", *Global Environmental Change*, Volume 17, Issues 3-4, 397-407

United Nations (1987), "Report of the World Commission on Environment and Development." General Assembly Resolution 42/187, 11 December 1987

Vaccaro G.L.R., Pohlmann, C., Lima, A.C., Santos, M., de Souza, C., Azevedo, D.,(2009), "Prospective scenarios for the biodiesel chain of a Brazilian state", *Renewable and Sustainable Energy Reviews*, 14, (4), 1263-1272.

Vaessen, J.(2006)," Programme Theory Evaluation, Multicriteria Decision Aid and Stakeholder Values: A Methodological Framework", *Evaluation*, Vol 12(4), 397-417.

Vahidnia, M. H., Alsheikh, A. A., Alimohamaddi, A.(2009), "Hospital Site Selection Using Fuzzy AHP and its Derivatives", *Journal of Environmental Management*, doi: 10.1016/j. Jenvman. 2009.04.010.

van Eijck, J. and Romijn, H. (2008), "Prospects for Jatropha biofuels in Tanzania: An analysis with Strategic Niche Management", *Energy*, Volume 36, Issue 1, 311-325.

van Laarhoven , P.J.M. and Pedrycz, W.(1983), " A fuzzy extension of Saaty's priority theory", *Fuzzy Sets and Systems* 11, 229-241,.

Venkateswarlu, J. (2001) "Management of soils in Andhra Pradesh." (Andhra Pradesh State, India: Acharya N.G. Ranga Agricultural University, Hyderabad.

Wang, Y.M., Luo, Y., Hua, Z., (2008), "On extent analysis for fuzzy AHP and its application", *European Journal of Operational Research*, 186, 735-747.

Wang, J. J., Jing, Y. Y., Zhang, C.F., Zhao, J. H., " Review on multi-criteria decision analysis aid in sustainable energy decision-making", *Renewable and Sustainable Energy Reviews* 13, 2263-2278.

Xu, R. (2000), "Fuzzy least-squares priority method in the analytic hierarchy process", *Fuzzy Sets and Systems*, Volume 112, Issue 3, 395-404

Zadeh, L.A. (2000), "Towards a perception-based theory of probabilistic reasoning" Plenary address at the July 2000 conference(abstract), North American Fuzzy Information Processing Society.

Zeleny, M. A.(1982), "Multi Criteria Decision Making"

APPENDIX 1: DATA TABLES (PHILIPPINES)

The data are taken from the following sources:

FAO Statistics: “The Philippines” Gateway to Land and Water Information
<http://www.fao.org/ag/agl/swl/wpnr/reports/y ta/z ph/ph.htm#use.2004>, YieldData:<http://www.fao.org/docrep/t4470e/t4470e05.htm>

Coconut: Chan and Elevitch, (2005) and <http://www.fao.org/docrep/t4470e/t4470e05.htm>

Sweet Sorghum: Elevation and % clay criteria have been retained from land resources issue. The data has been taken from <http://plants.usda.gov/java/charProfile?symbol=SOBI2>

http://www.icrisat.org/vasat/learning_resources/crops/sorghum/sorghum_prodpractices/html/m12/resources/1902.html and <http://www.fao.org/docrep/t4470e/t4470e05.htm>

Tropical Sugarbeet: <http://www.tnau.ac.in/tech/swc/sugbeet.pdf>

Sweet Potato: <http://www.fao.org/docrep/t4470e/t4470e05.htm>, Woolfe (1992) and Martin (1988).

Percentage Humus (Table A 1.6): Kurtner et. al (2008)

A1.1) Range of the Growing Season

Table 1.1 lists data on length of growing period measured in days in the country:

| Range | Linguistic Variable Assigned | Length in days |
|------------|------------------------------|----------------|
| Very Short | Very Low | 195 - 225 |
| Short | Low | 200 - 270 |
| Medium | Medium | 250 - 315 |
| Long | High | 300 - 345 |
| Very Long | Very High | 330 - 360 |

Table A1.1: Range of the Growing Season (in days)

A1.2) Temperature Regimes

Temperature regimes during the growing period are given in °C in the Table A1.2

| Range | Linguistic Variable Assigned | Mean Temperatures (in °C) |
|-----------|------------------------------|---------------------------|
| Very low | Very Low | 10-15 |
| Low | Low | 15-17.50 |
| Medium | Medium | 17.50 - 22.50 |
| High | High | 22.50 - 25.00 |
| Very High | Very High | >25.00 |

Table A1.2: Temperature Regimes (°C)

A1.3) Percent Clay

| With respect to texture, the types of soil include coarse, moderately coarse and fine based on the availability of percentage of clay present in the soil as shown in Table A1.4: Range | Linguistic Variable Assigned | Texture (% clay) |
|--|-------------------------------------|-------------------------|
| Coarse | Very Low | < 10 |
| Moderately coarse | Low | 10-20 |
| Moderately fine | Medium | 20-30 |
| Fine | High | > 30 |

Table A1.3: Soil Texture (based on % Clay availability)

A 1.4) Soil Depth

The criteria of soil depth is measured in terms of centimetres in Table A1.4.

| Range | Linguistic Variable Assigned | Soil Depth (cm) |
|--------------|-------------------------------------|------------------------|
| Very Shallow | Very Low | 0-10 |
| Shallow | Low | 10-25 |
| Medium Deep | Medium | 25-50 |
| Deep | High | 50-100 |
| Very Deep | Very High | 100 |

Table A1.4: Soil Depth (cm)

A1.5) Percentage Humus

This criterion represents the presence of nutritive, organic matter in the soil.

| Range | Linguistic Variable Assigned | Percent Humus |
|-------------------------|-------------------------------------|----------------------|
| Very Low | Very Low | 0-2 |
| Low | Low | 2-4 |
| Average | Medium | 4-6 |
| Increased Concentration | High | 6-8 |
| High Concentration | Very High | 8-10 |

Table A1.5: Percentage Humus (Kurtner et al.,08)

| A1.6) Number of River Basins | Linguistic Variable Assigned | Number of River Basins |
|------------------------------|------------------------------|------------------------|
| Very few | Very Low | 0- 5 |
| Moderately few | Low | 5-22 |
| Many | High | 20- 65 |
| Very many | Very High | > 63 |

Table A1.6: Number of River Basins

A1.7) Groundwater Resources Water Storage Capacity of Philippine Groundwater Resources of the Philippines is measured in terms of million cubic metres.

| Range | Linguistic Variable Assigned | Storage Capacity (1000*million cubic metres) |
|-----------|------------------------------|--|
| Very Low | Very Low | 0-2 |
| Low | Low | 3 - 5 |
| Medium | Medium | 5- 10 |
| High | High | 10- 20 |
| Very High | Very High | 20 |

Table A1.7: Groundwater Resources (million cubic metres)

A1.8) Natural Runoff

Available Water Supply of Natural Run-Off is measured in percentage as shown in Table A1.9.

| Range | Linguistic Variable Assigned | Percent Dependability (%) |
|-----------|------------------------------|---------------------------|
| Low | Low | 0-50 |
| High | High | 0-70 |
| Very High | Very High | 0-90 |

Table A1.8: Natural Runoff

A1.9) Elevation

| Range | Linguistic Variable Assigned | Elevation (m) |
|--------|------------------------------|---------------|
| Low | Low | 0- 100 |
| Medium | Medium | 100-500 |
| High | High | 500-2954 |

Table A1.11: Elevation (m)

A1.10) Slope

| Range | Linguistic Assigned | Variable | Slope (%) |
|--------------|--------------------------------|-----------------|------------------|
| Low | Low | | 0- 8 |
| Medium | Medium | | 0-18 |
| High | High | | 33-100 |

Table A1.12: Slope (%)

A1.11) Rainfall

| Range | Linguistic Assigned | Variable | Rainfall (mm) |
|--------------|--------------------------------|-----------------|----------------------|
| Medium | Medium | | 500-600 |
| High | High | | 750-1000 |
| Very High | Very High | | 1000-2000 |

Table A1.14: Rainfall (mm)

A1.12) Topographic Slope

Measured in terms of percentage (%)

| Range | Linguistic Assigned | Variable | Rainfall (mm) |
|-----------------|--------------------------------|-----------------|----------------------|
| Very Low | Very Low | | 0-1 |
| Moderately High | Medium | | 10-15 |
| High | High | | 15-33 |
| Very Steep | Very High | | 33-100 |

Table A1.15: Topographic Slope (%)

APPENDIX 2: DATA TABLES (INDIA)

INTRODUCTION

The depleting fossil fuels, the ever increasing demand for energy and the climate changes have led to biofuels being considered an alternative energy source (NEPAD, 2007). Governments world-wide are promoting biofuels because of their low prices, high yields and less negative impact on the environment (Water policy brief, 2007).

India is a rapidly growing economy. Second most populous country and in terms of energy demand ranked sixth, India imports approximately 75% of the crude oil to meet its energy demand (Punia, 2007). India has recently shifted its attention toward biofuels to avert a possible energy crisis.

DATA COLLECTION METHODOLOGY

A study of various research papers (both published and unpublished) and publications has been conducted for a statistical analysis of various parameters pertaining to biofuel crops. The utmost care has been taken to ensure credibility of the data. Authentic sources like the statistical and economic reports of the Indian Ministry of Agriculture and various UN agencies are used. This should provide a genuine knowledge bank regarding the biofuel crops where the area of study is as big as a country like India.

ASSUMPTIONS MADE

Assessment of the statistics related to different categories of miscellaneous parameters category has been made for bioethanol and biodiesel. Biodiesel is extracted from Jatropha, rapeseed, sunflower and soybean, whereas maize, sugarcane and sweet sorghum produce ethanol. As all the crops produce either bioethanol or biodiesel and the acquisition of

individual statistics for each parameter is not possible, a generalized assessment of bioethanol and biodiesel has therefore been made.

The calculations are based on the assumption that they were taken under optimum condition.

The actual readings might differ substantially from the reported ones.

LOOPHOLES IN DATA

Most of the specific data like ‘the land under cultivation’ and ‘yield’ have been taken from the Agriculture ministry of India but the less specific data like ‘pH requirements’, and ‘temperature requirements’ are generalized. This is due to the fact that the concept of biocrops and biofuel is fairly new to India. The government is yet to establish official statistics for such parameters.

As biocrop cultivation has recently been undertaken in India; therefore, most of the data in the economic parameters category is conceptual and generalized. This data may vary highly from the actual data hence limiting this essay to various biocrops comparisons only.

| | Jatropha | Maize | Rapeseed | Sweet Sorghum | Soybean | Sugarcane | Sunflower | P Low | P High |
|--|-------------------------|-------------|-----------|---------------|-----------|---------------|-----------|-------|--------|
| Agricultural Parameters | | | | | | | | | |
| Land under cultivation (million hectares) ^[a] | 0.4-0.45 ^[d] | 7.43-7.59 | 7.28-7.32 | 29.03-29.04 | 7.57-7.71 | 3.66-4.20 | 2.17-2.34 | 0.40 | 29.04 |
| Produce (million tonnes) ^[a] | NA | 14.17-14.71 | 7.59-8.13 | 33.44-34.07 | 6.87-8.27 | 237.08-281.17 | 1.19-1.44 | 1.19 | 281.17 |

| | | | | | | | | | |
|--|-------------------------|-----------|-----------------------|-----------|----------|-------------|-----------|-----|-------|
| Yield/hectare (Kg/ha) ^[a] | 3750 ^[d] | 1907-1938 | 1038-1117 | 1153-1172 | 908-1073 | 64752-66928 | 549-615 | 549 | 66928 |
| %Coverage Under Irrigation ^[a] | NA | 20.5-21.1 | 69.3-72.1 | 6.6-13.0 | 1.7-1.8 | 91.2-95.2 | 24.9-26.0 | 1.7 | 95.2 |
| Precipitation tolerance (dm/annually) ^[b] | 3.0-10.0 ^[d] | 2.3-41.0 | 3.0-28.0 | 2.0-21.4 | 3.1-41.0 | 4.7-42.9 | 2.0-40.0 | 2.0 | 42.9 |
| Water requirement (mm/annum) ^[c] | 300-1000 ^[d] | 550-750 | 80-240 ^[g] | 400-750 | > 600 | 750-1200 | 550 | 80 | 1200 |
| Soil pH requirement ^[b] | 5.0-7.0 | 4.3-8.7 | 4.2-4.8 | 4.9-8.2 | 4.3-8.4 | 4.3-8.4 | 4.5-8.7 | 4.2 | 8.7 |
| Nitrogen Fertilizers (GJ/ha) ^[f] | NA | NA | 4.6-9.2 | NA | 0-7.6 | NA | 5.3-9.2 | NA | NA |

Table 1. Data analysis of various agricultural parameters for seven biofuel crops grown in India.

| | Jatropha | Maize | Rapeseed | Sweet Sorghum | Soybean | Sugarcane | Sunflower | P Low | P High |
|---|----------------------|-------------|---------------------|---------------------|---------------------|--------------------|---------------------|-------|--------|
| Environmental Parameters | | | | | | | | | |
| Oil content (%) ^[c] | 43-59 ^[d] | 75 (starch) | 35-40 | 25-35 | 18-22 | 80 (starch) | 40-48 | 25 | 80 |
| Oil yield (litres/ha) ^[k] | 1892 ^[d] | 172 | 1190 | 6000 | 446 | 5052 | 952 | 172 | 6000 |
| Total energy obtained (GJ/ha) | 49.9 ^[d] | NA | 41.7 ^[p] | 42.5 ^[r] | 31.9 ^[q] | 139 ^[s] | 59.7 ^[t] | 31.9 | 139 |
| Total energy input (GJ/ha) ^[f] | NA | 25-40 | 13-37 | 15-50 | 15-35 | NA | 20-38 | 15 | 50 |

| | | | | | | | | | |
|---|-----|-------|------|-----|------|------|-----|------|------|
| Water Footprints (m ³ /GJ biofuel) ^[h] | 574 | 110 | 165 | 419 | 177 | 108 | NA | 108 | 574 |
| Energy balance ^[e] | NA | 1.5 | 2.7 | NA | 3 | 8.3 | 3.2 | 1.5 | 8.3 |
| GHG emission (kg CO ₂ /MJ) ^[i] | NA | 81-85 | 37 | NA | 49 | 4-12 | NA | 4 | 85 |
| GHG emission reduction (kg CO ₂ eq/litre) ^[j] | NA | 1.13 | 2.89 | NA | 2.39 | 1.7 | NA | 1.13 | 2.89 |

Table 2. Data analysis of various environmental parameters for seven biofuel crops grown in India.

| | Jatropha | Maize | Rapeseed | Sweet Sorghum | Soybean | Sugarcane | Sunflower | P Low | P High |
|--|--|-------|----------|---------------|---------|-----------|-----------|-------|--------|
| Economic Parameters | | | | | | | | | |
| Cost of cultivation (US \$/ha/yr) ^[m] | NA | NA | NA | 400 | NA | 995 | NA | 400 | 995 |
| Net returns (US \$/ha/yr) ^[n] | 300 | NA | 302.66 | 986 | 337.6 | 1700 | 437.1 | 300 | 1700 |
| Biofuel Plantation employment (millions/day) | 127.6 (Estimated) ^[o] | | | | | | | | |
| Biodiesel production cost in India (US\$/Kg) | 0.558 | | | | | | | | |
| Value added by products | Biofuels are yet to be commercialised in India | | | | | | | | |

Table 3. Data analysis of various economic parameters for seven biofuel crops of India.

| | Jatropha | Maize | Rapeseed | Sweet Sorghum | Soybean | Sugarcane | Sunflower | P Low | P High |
|---|-----------------------|---------|----------|--------------------|----------|--------------------|-----------|--------|--------|
| Miscellaneous Parameters | | | | | | | | | |
| Cetane number ^[k] | 46-70 ^[d] | 53 | 55-58 | 8-9 ^[l] | 53 | 8-9 ^[l] | 52 | 8 | 70 |
| Iodine value ^[k] | 60-135 ^[d] | 115-124 | 97-115 | NA | 125-140 | NA | 125-135 | 60 | 135 |
| Cloud point (°C) ^[l] | -11 - 16 | -8 - 22 | -11 - 16 | -8 - 22 | -11 - 16 | -8 - 22 | -11 - 16 | -11 | 22 |
| Flash point (°C) ^[l] | 122 | 13 | 122 | 13 | 122 | 13 | 122 | 13 | 122 |
| Pour point (°C) ^[l] | 9 | -117.3 | 9 | -117.3 | 9 | -117.3 | 9 | -117.3 | 9 |
| Heat of combustion (MJ/kg) ^[l] | 39.6 | 27 | 39.6 | 27 | 39.6 | 27 | 39.6 | 27 | 39.6 |

Table 4. Data analysis of various miscellaneous parameters for seven biofuel crops of India.

REFERENCES FOR APPENDIX DATA

^[a]Area, production and yield of major crops. (2008) Agriculture Ministry of India. Available at: http://dacnet.nic.in/eands/At_Glance_2008/pcrops_new.html (Accessed on 21/12/2009)

^[q]Billore SD, Joshi OP, Dupare BU (2004) Impact of frontline demonstrations on augmenting the soybean, *Glycine max L.* productivity. *J Oilseeds Res* 21 : 352-353

^[d]Center for Jatropha promotion and biodiesel. Available at: www.jatrophaword.org (Accessed on 21/12/2009)

^[p]Chaudhary AK, Badiyala D, Negi PS (2002) Comparative performance of Brassica species to varying fertility levels under mid-hill conditions of Himachal Pradesh. *J. Oilseeds Res* 19 : 123-124

^[i]Cornell, C. B. (2008) How green are biofuels? Available at: <http://gas2.org/2008/05/08/how-green-are-biofuels-comparison-chart-pic/> (Accessed on 22/12/2003)

^[b]Duke, J.A. (1983) *Handbook of Energy Crops* (Unpublished) Available at: http://www.hort.purdue.edu/newcrop/Indices/index_ab.html (Accessed on 22/12/2009)

^[h]Gerbens-Leenes, W. Hoekstra, A. Y. and van der Meer, T. H. (2008) The water footprints of bioenergy. Available at: www.pnas.org/cgi/doi/10.1073/pnas.0812619106 (Accessed on 21/12/2009)

^[j]GHG Emission Reduction from World Biofuel Production and Use- A Report (2009) Available at:

http://www.globalrfa.org/pdf/120809_final_report_ghg_emissions_biofuels_1.pdf (Accessed on 22/12/2009)

^[o]Gonsalves, J. B. (2006) An assessment of biofuels industry in India. Report for UNCTAD Available at: <http://www.biotechnologie.de/BIO/Redaktion/PDF/de/laenderfokus/indien-biofuel-unctad.property=pdf,bereich=bio,sprache=de,rwb=true.pdf> (Accessed on 21/12/2009)

^[g]Kumar, A. Chauhan, J. S. and Chattopadhyay, C. (Eds.) (2008) *Sustainable Production of Oil Seeds: Rapeseed-Mustard Technology*. India. Agrotech Publishing Company

^[l]Kwanchareona, P. Luengnaruemitchaia, A. and Jai-Inb, (2006) S. Solubility of a diesel–biodiesel–ethanol blend, its fuel properties, and its emission characteristics from diesel engine. *Fuel* Vol. 86

^[s]Misra A, Tripathi BK (2006) Feasibility of mechanical harvesting of sugarcane (*Saccharum* spp. Hybrid) *Ind J Agron* 51 : 65-67

^[r]NATP (2004) Annual Report of RNPS-24 entitled, “Developing sorghum as an efficient biomass and bio-energy crop and providing value addition to the rain damaged kharif grain for creating industrial demand. National Research Center for Sorghum Rajendranagar Hyderabad pp 31

^[c]NEPAD and FAO. Biofuels (Bioethanol and Biodiesel) Crop Production: Technology Options for Increased Production, Commercialisation & Marketing (2007) Available at: <ftp://ftp.fao.org/docrep/fao/010/ah917e/ah917e00.pdf> (Accessed on 21/12/2009)

^[n]Nimbkar Agricultural research Institute. Available at: <http://www.nariphaltan.org/nari/>

^[k]Oil yield and characteristics. Available at: http://journeytoforever.org/biodiesel_yield.html (Accessed on 21/12/2009)

^[m]Pro-Poor Biofuels Outlook for Asia and Africa: ICRISAT’s Perspective (2007) Available at:

<http://docs.google.com/viewer?a=v&q=cache:aiG12wVE6OsJ:test1.icrisat.org/Investors/Biofuel.pdf+total+land+cultivated+for+use+of+biofuels&hl=en&gl=in&pid=bl&srcid=ADGEESHMONATd9vYfRbbGnxwzHCWWKrGTAd0OBM8mrwJTBmXwDfGpehUFXKXSzHs8gS8CnN-FCOYZAjeDibomgKiBjq1eInM5GPOyjQfzNv1ht5Z16CG3JWYakmlt1jufi0JHtAZ4a4&sig=AHIEtbT9EY-bfXNWRg7WlCnml0tZqVHN2Q> (Accessed on 22/12/2009)

Punia, M. S. (2007) Cultivation and use of *Jatropha* for Bio-Diesel production in India. Available at:

<http://www.cpamn.embrapa.br/agrobioenergia/palestras/CULTIVATION%20AND%20USE%20OF%20JATROPHA%20FOR%20BIO-DIESEL%20PRODUCTION%20IN%20INDIA.PDF> (Accessed on 21/12/2009)

^[1]Reddy B. N., Babu S. N., Ravishankar, G., Sahadeva Reddy, B., Jayapradha, A. (2002) Effect of levels of nitrogen and phosphorus on the performance of sunflower (*Helianthus annuus* L) in rice fallow vertisols. *J Oilseeds Res* 19 : 226-228

^[1]Venturi, P. and Venturi, G. (2003) Analysis of energy comparison for crops in European agricultural systems. *Biomass and Bioenergy* Vol. 25

Water implications of biofuel crops: understanding tradeoffs and identifying options. Water Policy Brief. Issue 30. Available at:

http://www.iwmi.cgiar.org/Publications/Water_Policy_Briefs/PDF/WPB30.pdf (Accessed on 22/12/2009).