Assessment of Sustainable Forest Management Using Fuzzy Rule-Based Model

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by

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Abstract

Assessment of sustainable forest management (SFM), especially through forest certification scheme, requires a decision making method that can help decision maker to judge whether or not a forest management unit (FMU) is managed in a sustainable manner. One of the decision making methods that currently used in the Indonesian forest certification system (called LEI system) is Analytic Hierarchy Process (AHP). Despite easy to use, the AHP has some shortcomings such as inability to handle imprecise judgments, allows compensation, and impracticality of its pairwise comparison method. Considering such issues, this study was aimed at developing a fuzzy rule-based (FRB) model as an alternative decision making method to assess SFM using the LEI system. In this study, the hierarchical criteria and indicators of ecological sustainability of the LEI system was used as main architecture of the FRB model. Moreover, the expert knowledge was used to generate rule base which provides logical thinking and reasoning on how to aggregate linguistically various verifiers, indicators, and criteria of ecological sustainability. In general, the FRB model was developed through four main steps, namely: normalization, fuzzification, fuzzy inference, and defuzzification. To analyze effect of membership functions to the model outputs, an analysis was carried out by adopting different membership functions derived from the pairwise comparison matrices and then compared to those derived arbitrary. Furthermore, comparisons with the existing method (AHP) were carried out using the real assessment data and the hypothetical data. The results of this study were two FRB models: the FRB-1 model which uses inputs at the indicators level and the FRB-2 model which uses inputs at the verifier level. The FRB-1 model which was tested using the real data could give the same grade of certification as that of the AHP method. The analysis of membership functions revealed that different shape of membership functions could lead to different outputs. It was proved that membership functions derived from the pairwise comparison matrices could give more reasonable results than those derived arbitrary. Moreover, the results of this study showed that compensation would not occur when assessment is carried out using the FRB model. In addition, the FRB-2 model provides an alternative approach in which decision maker could make an assessment directly based on the verifier values. In overall, this study has showed that the FRB model is a promising tool for assessing ecological sustainability of SFM with reasonable results.

Keywords: sustainable forest management (SFM), fuzzy rule-based (FRB) model, analytic hierarchy process (AHP), forest certification, LEI system

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Chapter 1

Introduction

1.1. Background

Sustainable forest management (SFM) has become a new paradigm and an ultimate goal in managing forests worldwide. In the past, forest management was mainly focused on achieving sustained yield of timber (Boncina, 2000; Castañeda, 2000; Rametsteiner, 2001). Nowadays, in line with the SFM concept, forest management should emphasize on achieving sustainability of all forest functions, i.e. economic, environmental, social and cultural dimensions (Boncina, 2000; Castañeda, 2000; Rametsteiner and Simula, 2003). Indeed, paradigm of forest management has shifted from timber-based management into ecosystem-based and community-based management.

In practice, it is not easy to implement SFM concept. One of the reasons is due to the fact that there is no universally accepted definition (Raison et al., 2001; Vogt et al., 2000) that can give common understanding about SFM. In this case, development of criteria and indicators (C&I) for SFM is a significant effort that has been made by many international organizations to further "clarify what is meant by SFM in practice" (Rametsteiner, 2001). The C&I are one of several tools which provide a framework for conceptualizing, assessing, and monitoring SFM (Castañeda, 2000; Prabhu et al., 2001), with which we may be able to judge whether or not a particular forest management is sustainable. One of the C&I sets for SFM of tropical forests is the ITTO (International Tropical Timber Organization) which presented a list of seven criteria and 66 indicators that are applicable to both national and forest management unit levels (ITTO, 1998). The comprehensive overview and further analysis of various C&I sets can be found in Bueren and Blom (1996) and Vogt et al. (2000).

In line with development of C&I sets, forest certification has been introduced as a significant instrument to promote SFM. The idea of forest certification is that timber and other wood products, which are traded worldwide, should come from well-managed forests. Accordingly, forest certification would be able to promote SFM by informing consumers about sustainability of the forest management behind wood products (Veisten, 2002) as well as by motivating producers to demonstrate that their forests are being managed in a sustainable manner (Vogt et al., 2000). Usually, the certification process is conducted by an independent third party (called certification body) who assesses and ensures that the quality of forest management complies with a certain standard, i.e. criteria and indicators for SFM (Rametsteiner and Simula, 2003).

Although forest certification seems to be a promising way towards achieving SFM, there are still a lot of problems in its implementation, particularly regarding how to assess SFM.

As pointed out by Rametsteiner (2001), the procedures for weighing, aggregating, and determining threshold values for criteria and indicators are often not clearly defined and this may lead to hesitancy on the results of certification. The difficulties in assessing SFM may emerge because the concept of SFM itself is vague and not easily quantified (Vogt et al., 2000). The assessment of criteria and indicators, such as scoring and weighing processes, may also involve high subjectivity (Bueren and Blom, 1996; Vogt et al., 2000), because not all indicators can be quantified and measured exactly. Another issue is that the assessment would deal with uncertainty, for instance due to complexity of the problems, which is inevitable in any forestry decisions (Kangas and Kangas, 2004).

To date, still relatively little research has been focused on developing a formal method for evaluating SFM (Prabhu et al., 2001). Therefore, there is still room for developing decision making method for assessing SFM (Bueren and Blom, 1996; Rametsteiner, 2001), particularly in the context of forest certification. Such decision making method should be able to handle vagueness of SFM concept (Vogt et al., 2000), address uncertainty which is attached to the C&I (Prabhu et al., 2001), accommodate mixed sets of data both quantitative, qualitative and expert opinions (Mendoza and Prabhu, 2003), and provide cost-effective information as well as justifiable results (Prabhu et al., 2001; Vogt et al., 2000).

One appropriate decision making method that could be used to assess SFM is the ***fuzzy rule-based approach***, which is a branch of fuzzy logic theory developed by Zadeh (1965). Many scientists, such as Ducey and Larson (1999), Cornelissen et al. (2001), Phillis and Andriantiatsaholiniaina (2001), Reynolds et al. (2003), Mendoza and Prabhu (2004), and Adriaenssens et al. (2004), considered that the fuzzy logic approach (especially the fuzzy rule-based approach) seems to be an appropriate and promising method to assess sustainability issues such as SFM. Indeed, this theory is designed to model the vagueness and impreciseness of human judgments (Lootsma, 1997), which are also common issues in assessing SFM.

1.2. Research Problem

In Indonesia, forest certification has been initiated in 1994 by Lembaga Ekolabel Indonesia (LEI, Indonesian Ecolabeling Institute), a non-governmental organization. In 1999, the LEI developed a set of C&I for SFM of natural production forests, which consists of three principles, ten criteria and 57 indicators (see ***Section 2.2***). This C&I set is used as a standard to assess SFM of natural production forests in Indonesia through forest certification scheme.

In the LEI system, the decision making method which is used to determine the final certification grades, is the Analytical Hierarchy Process (AHP), a popular decision making method developed by Thomas L. Saaty (Saaty, 1980; Saaty, 1986; Yoon and Hwang, 1995). The LEI claimed that the AHP would provide objectivity, repeatability, and transparency in the decision making process on forest certification (LEI, 2000). Indeed, in some aspects, the AHP is an easy decision making tool to solve complex problems. However, the AHP also has some shortcomings related to its theoretical properties and its practical issues.

From the theoretical viewpoint, one of its shortcomings is inability to handle the inherent uncertainty in imprecise judgments (Deng, 1999; Leung and Cao, 2000; Lootsma, 1997) because the AHP requires decision makers to express their preferences using crisp numbers. Another issue, AHP is a compensatory method (Forman and Selly, 2002; Sharifi et al., 2004) because its aggregation process uses a weighted summation method (Belton and Gear, 1983; Triantaphyllou, 2000; Yoon and Hwang, 1995) which allows a good performance criterion to compensate a bad performance criterion. In the context of forest certification, such compensatory phenomenon should be looked at carefully because in some cases we could not justify that the bad performance indicators can be compensated by other good performance indicators. For instance, performance of the area affected by forest fire could not be compensated by having a good early warning system.

In the practical viewpoint, one of the AHP's shortcomings is the number of pairwise comparisons in eliciting input values (Kumar and Ganesh, 1996; Triantaphyllou, 2000). The AHP requires the decision maker to structure a problem into a hierarchy which consists of several elements and then compare a particular element to all the other ones with respect to a certain objective, which one is the most important and how important it is. Then, a decision maker should assign a crisp value ranged from 1 (equally important) to 9 (extremely important) for each comparison (see ***Section 2.3*** for an overview of the AHP). Such comparison would become impractical when the number of entities (i.e. alternatives or criteria) that has to be compared becomes large. If there are ***n*** entities, then the decision maker should make ***n(n-1)/2*** pairwise comparisons (Triantaphyllou, 2000). For the LEI system there would be 581 pairwise comparisons, which may lead to increased subjectivity and inconsistency of the expert judgments and is time consuming as well.

Considering those problems, therefore, it is necessary to develop an alternative decision making method for assessing SFM using the LEI system. This study considers that the *fuzzy rule-based model* can be used as an alternative method based on the following considerations:

- In the LEI system, criteria and indicators of SFM are assessed using expert knowledge. In this context, the fuzzy rule-based model would be able to emulate logical thinking of the experts by modeling interrelationship among the C&I components using natural language.
- The experts judge the indicator values using linguistic terms, such as *excellent*, *good*, *fair*, *poor*, and *bad*, so that the vagueness would attach in such values. The fuzzy rule-based model is able to handle the vagueness in linguistic terms as well as accommodate subjectivities and impreciseness of the expert judgments.
- The fuzzy rule-based model is based on a human way of thinking (Sugeno and Yasukawa, 1993), hence the experts would have control on how to aggregate the indicator values based on their way of thinking instead of using numerical aggregation. This could address compensatory phenomenon of the AHP method.

Actually, research on application of fuzzy rule-based model for the LEI system has been initiated by Jeganathan (2003) and Kuswandari (2004) who worked only with a part of the LEI's hierarchy (i.e. sustainability of production functions). This study intends to follow up their work to cover the other parts of the LEI's hierarchy, namely sustainability of ecological functions (see ***Figure 1.1***), so that it would provide more comprehensive application of the fuzzy rule-based model for the LEI system. Moreover, this study will also enhance the application of the fuzzy rule-based model by addressing the compensation issue and developing a model with inputs at the verifier level. These issues have not been addressed yet in the previous studies.

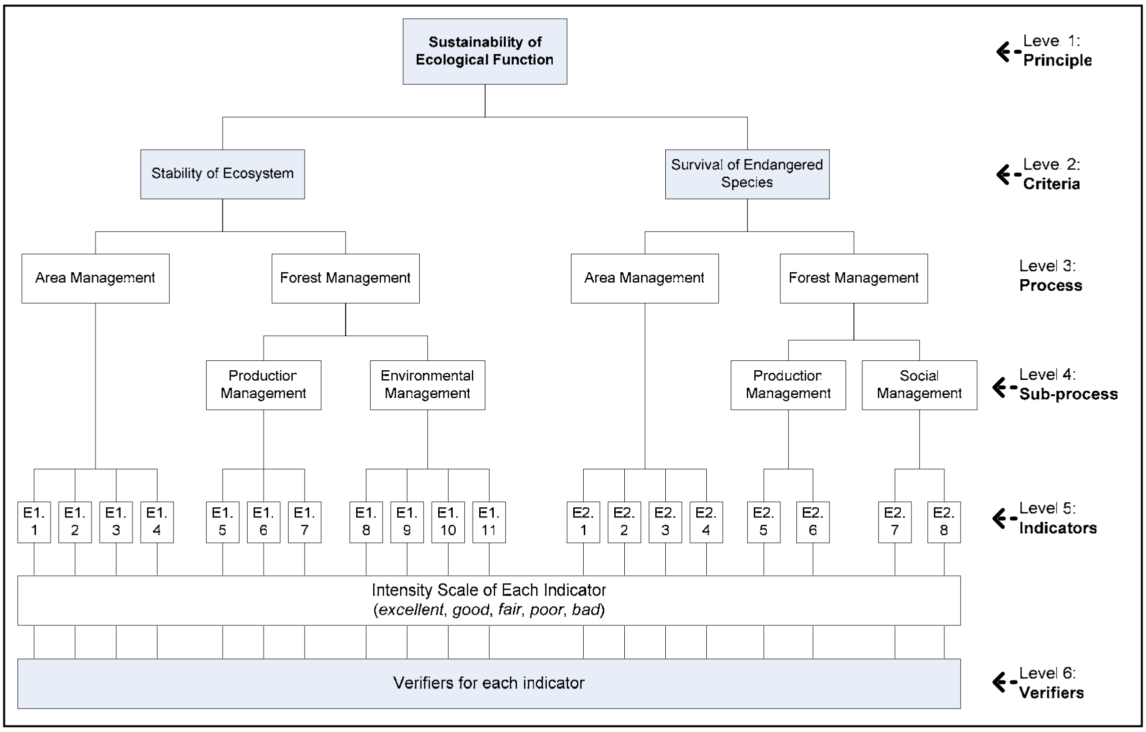


Figure 1.1. The hierarchical structure of sustainability of ecological functions (LEI, 2000)

1.3. Research Objectives

The main objective of this study is to develop a fuzzy rule-based model as an alternative decision making method for assessing sustainability of ecological functions of SFM using the LEI system.

The specific objectives are:
1. To obtain a (fuzzy) rule base which provides logical thinking and reasoning on how to assess sustainability of ecological functions of SFM based on expert knowledge.
2. To find out an appropriate approach to build membership functions for the fuzzy rule-based model.
3. To analyze strengths and weaknesses of the fuzzy rule-based model as an alternative decision making method for assessing SFM using the LEI system.

1.4. Research Questions

The research questions that related to the objectives are:

1. What shall be the rule base to be used for assessing sustainability of ecological functions of SFM?
2. What shall be the fuzzy rule-based models used to aggregate values of indicators and verifiers?
3. How to build membership functions for the fuzzy rule-based model which could give reasonable results?
4. Can the fuzzy rule-based model give reasonable results and address the compensation issue?
5. What are strengths and weaknesses of the fuzzy rule-based model?

1.5. Research Approach

In this study, the C&I set of the LEI system as depicted in ***Figure 1.1*** is used as a model to assess ecological sustainability of SFM in the Labanan forest management unit (FMU). There are three sources of data used in this study, namely the expert knowledge, the C&I set and the field assessment data. The expert knowledge and the C&I set are main sources to derive rule base for assessing ecological sustainability using the fuzzy rule-based model. The assessment is carried out using the fuzzy rule-based model as well as the existing method (AHP), so that any differences in the final outputs obtained from those methods can be analyzed. Furthermore, strengths and weaknesses of the proposed method can be analyzed and the important findings can be recommended. ***Figure 1.2*** depicts general approach used in this study.

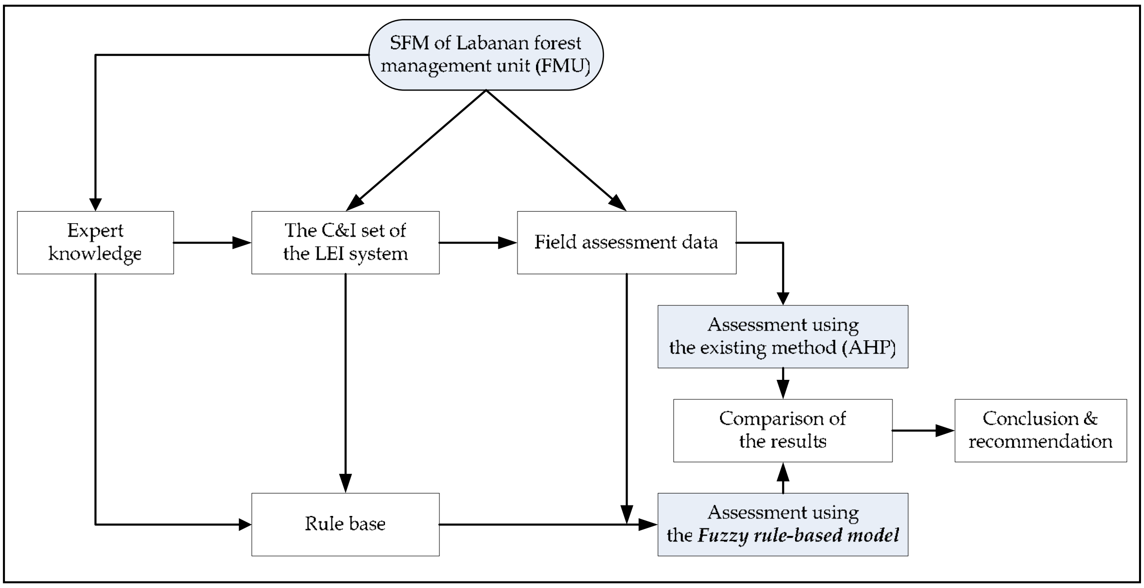


Figure 1.2. Research approach

1.6. Outline of the Thesis

This thesis consists of five chapters and some appendices. Chapter 1 explains background information related to the sustainable forest management (SFM) issues, the urgency of developing an alternative decision making method for the LEI system, the objectives and the research questions, and the general approach used in this study. Chapter 2 explores relevant literature related to SFM, forest certification in the LEI system, and basic concepts of the AHP method as well as the fuzzy logic theory. Chapter 3 describes the study area and the methods used to develop the fuzzy rule-based (FRB) model. In Chapter 4, the results obtained from the FRB model are discussed and then compared to those obtained from the existing method (AHP). Finally, Chapter 5 draws conclusions of this study and suggests recommendations for future study. In addition, the appendices present description of the ecological verifiers and indicators of the LEI system, the decision tree of the rule base, and the data used in this study.

Chapter 2

Literature Review

This chapter presents some background information related to concepts, definitions, and theories used in this study. The first section describes briefly about concept of sustainable forest management (SFM) and development of criteria and indicator (C&I) and forest certification as tools for promoting SFM. Since this study deals with forest certification in the LEI system, the second section explains briefly about this system with focus on the LEI's C&I, role of a certification body, certification procedure, and decision making process. The third section gives an overview about general concept of the Analytic Hierarchy Process (AHP) with illustrations of its application in the LEI system. In addition, the last section provides basic concept of fuzzy logic theory which serves foundations for developing fuzzy rule-based model. Both AHP and fuzzy logic are fundamental theories for this study.

2.1. Towards Sustainable Forest Management

Sustainable forest management (SFM), regardless its diverse definitions, could be defined as *"the process of managing forest to achieve one or more clearly specified objectives of management with regard to the production of a continuous flow of desired forest products and services without undue reduction of its inherent values and future productivity and without undue undesirable effects on the physical and social environment"* (ITTO, 1998). From this definition, it is obvious that SFM would be a promising strategy to achieve sustainability of all forest functions. In the SFM, sustained yield of wood or timber is not a primary goal anymore as practiced in conventional forest management in the past.

The concept of SFM emerged from the notion of sustainable development which was presented in Brundtland's report in 1987 (Wang, 2004). Since then, the SFM concept became an interesting issue in many international policy arenas as a global awareness of forest and environmental degradation in the world. The most important international policy arena that has promoted the SFM issue was the United Nations Conference for Environment and Development (UNCED) on 'Forest Principle' that was held in Rio de Janeiro, Brazil, in 1992 (Castañeda, 2000; Rametsteiner, 2001). Following the UNCED, many international initiatives have been involved in developing criteria and indicators (C&I) for SFM, such as: 1) the International Tropical Timber Organization (ITTO) which developed the guidelines for SFM of tropical forests, 2) the European Union (EU) through the Helsinki Process in 1993 which developed the European criteria and indicators of SFM for temperate countries, and 3) the Montreal Process which developed C&I of SFM for the temperate and boreal forests of non-European countries (McDonald and Lane, 2004; Vogt et al., 2000).

Criteria and indicators (C&I) is a primary instrument for implementing, measuring and monitoring SFM. In this context, ITTO (1998) defined a criterion as *"an aspect that is considered important by which sustainable forest management may be assessed"*, while an indicator is *"a quantitative, qualitative or descriptive attribute that, when periodically measured or monitored, indicates the direction of change"*. The C&I set which has been developed by some international organizations may have different components. However, in general they came to a global convergence to further clarify the SFM concept. In this context, McDonald and Lane (2004) have compared and analyzed the C&I of Montreal, European and ITTO, and concluded that these C&I sets are very similar. They cover seven essential aspects of SFM, namely: "conservation of biological diversity, maintenance of the productive capacity of forest ecosystems, maintenance of forest ecosystem health, conservation and maintenance of soil and water resources, maintenance of forest contribution to global carbon cycles, maintenance and enhancement of long-term multiple social and economic benefits, and legal institutional and economic framework for forest management."

In practice, the criteria and indicators (C&I) share the aim of promoting SFM with another instrument, namely forest certification. Rametsteiner and Simula (2003) defined forest certification as "*the process whereby an independent third-party (called a certifier or certification body) assesses the quality of forest management in relation to a set of predetermined requirements (the standard)*". The forest certification was introduced in 1993 as a market-based response to address deforestation in the tropics.

There are some differences between the C&I and the forest certification in terms of scale, purpose and user group. Most of the C&I sets are applied in national level, whereas the forest certification is exclusively applied in forest management unit (FMU) level. The purpose of the C&I sets are elaborated to describe the status of SFM and mainly used by governments and policy makers for information sharing, while the forest certification is essentially based on prescriptive standards and used by market players for providing proof of sustainable or good forest management (Rametsteiner and Simula, 2003).

2.2. Forest Certification in the LEI system

As response to promote SFM in Indonesia, LEI has developed a forest certification system since 1994. The certification system consists of four main components, namely: a C&I set for SFM, role of a certification body, certification procedure, and decision making process. Further information about this system can be found in LEI (2000). The following sections explain briefly each system component. The decision making process, which is also a part of the certification procedures, is explained in more details since it is a main issue of this study.

2.2.1. Criteria and indicators (C&I) for SFM

In 1999, LEI published the criteria and indicators (C&I) as a standard to assess sustainable natural production forest management (SNPFM) in Indonesia. The LEI's C&I set consists of 3 principles, 10 criteria, and 57 indicators as summarized in ***Table 2.1*** (see also ***Figure 2.1***).

Table 2.1. Principle, criteria and number of indicators of the LEI system (LEI, 2000)

Principle	Criteria	Number of indicators
1. Sustainability of production functions	1.1. Sustainability of forest resources 1.2. Sustainability of forest products 1.3. Sustainability of businesses	21
2. Sustainability of ecological functions	2.1. Stability of the ecosystem 2.2. Survival of endemic/endangered/protected species	19
3. Sustainability of social functions	3.1. Guaranteed community-based forest tenure system 3.2. Guaranteed resilience and economic development of community and employees 3.3. Guaranteed continuity of social and cultural integrity of community and employees 3.4. Realization of responsibility to rehabilitate nutritious status and prevent the impact on health 3.5. Assurance of employees' rights	17

The detailed description of each criteria as well as indicators of the LEI system can be found in LEI (2000). For the purpose of this study, ***Appendix A*** provides detailed descriptions of the ecological indicators.

As seen in ***Figure 2.1***, in the LEI system there are two additional levels in the hierarchy (except the principle, criteria, and indicator levels as commonly found in other C&I sets), namely process and sub-process levels. These levels emphasize that the goal can be achieved by implementing three main activities of management, namely area management, forest management, and institutional arrangement. Therefore, the indicators in the LEI system have been arranged in such a way to represent those main activities. In the field, the indicators are assessed by using verifiers. In the LEI system, the verifiers are not legally binding which means that assessors can either use the available verifiers as presented in the guideline or develop the other ones to come up with a value for an indicator. The value of each indicator is expressed using the five intensity scales (norms), namely *excellent*, *good*, *fair*, *poor*, and *bad* (LEI, 2000).

2.2.2. Role of a certification body

In the forest certification scheme, LEI acts as an accreditation body and a developer of forest certification system for SFM. The system is operated by a certification body, which is an independent organization that has been accredited by LEI to carry out the certification process in a forest management unit (FMU). In a certification body, there are two main actors who play important roles in a certification process, namely: 1) assessors who carry out field assessment, and 2) expert teams who have authorities in decision making process. To ensure that the system will be implemented properly by a certification body, LEI has developed some standards consisting of general requirements for a certification body, which are documented in LEI (2000). Moreover, LEI also provides training for assessors and expert teams to improve their capabilities in conducting a certification process using the LEI system.

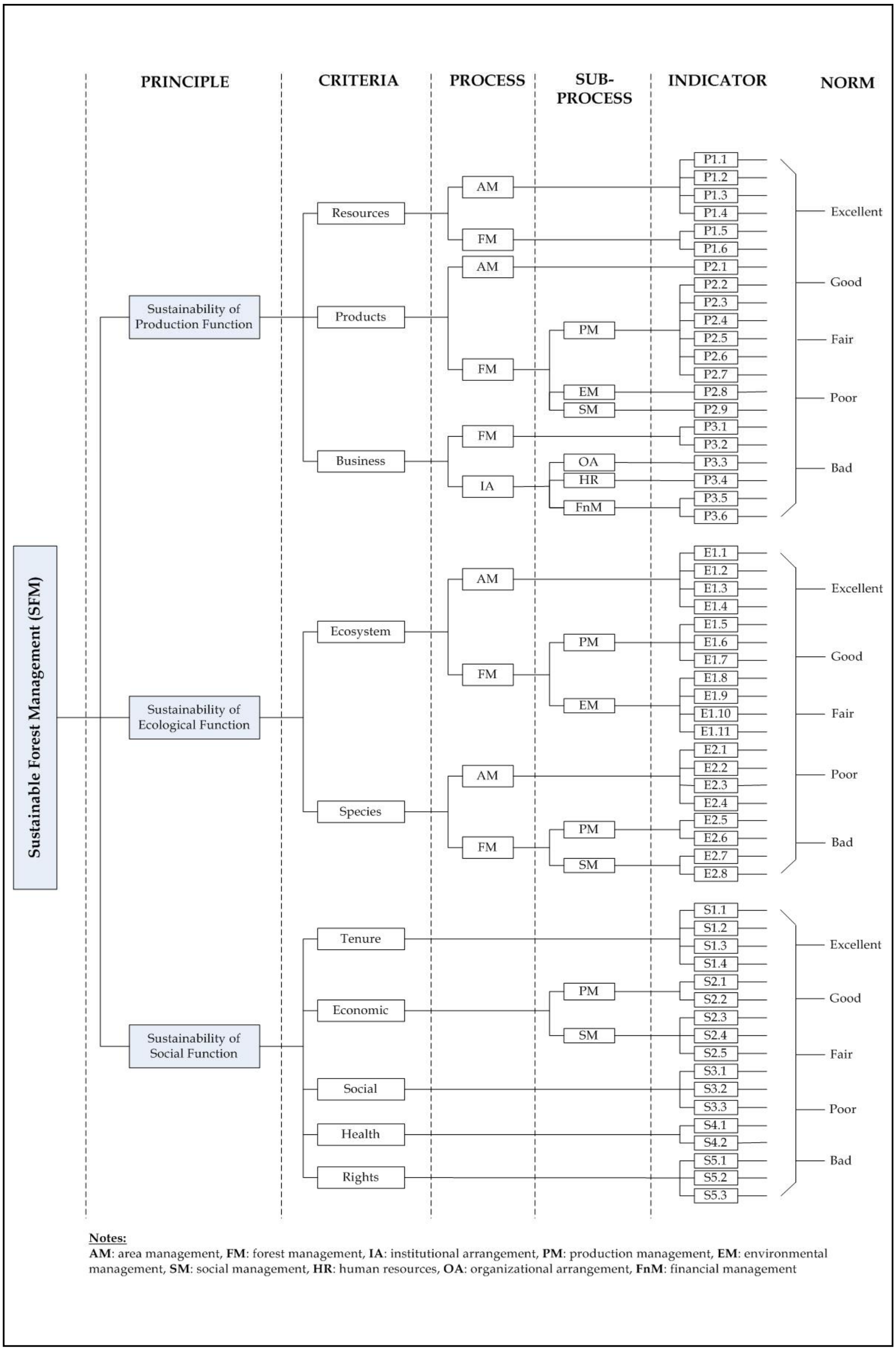


Figure 2.1. The structural hierarchy of criteria and indicators of the LEI system to assess SNPFM (adopted from: LEI, 2000; Purbawiyatna, 2002)

2.2.3. Certification procedure

The certification process is carried out by an eligible certification body. In general, the certification process consists of four steps (LEI, 2000):

1. Pre-assessment
   This step aims at collecting basic information to verify whether or not a forest management unit (FMU) has fulfilled basic requirements for the certification process. The pre-assessment, which is carried out by an expert team (called Expert Panel I), consists of a series of activities, namely assessing relevant documents, field visit to the concession area, and decision making. Based on such assessment the certification body makes decision whether or not the FMU should proceed to the certification process.

2. Field assessment and public consultation
   Once the FMU is accepted, field assessment will be carried out by a group of assessors from the certification body to collect data and information about performance of the FMU. In this step, the criteria and indicators are used for assessing actual condition of the FMU activities. In addition, the certification body should also offer opportunities for public consultation to gain inputs from communities, particularly concerning positive and negative impacts from the FMU activities. Such inputs are also used as a main consideration to make final decision of certification.

3. Decision making process
   Decision making process is carried out to evaluate performance of forest management unit with respect to criteria and indicators of SNPFM. The main inputs for this step are field assessment report, inputs from communities, and the results of pre-assessment at the first step. Based on such performance evaluation, an expert team (called Expert Panel II) makes a final certification decision and relevant recommendations. Since this study concerns with the decision making process, hence detailed process of this step is further explained in ***Section 2.2.4***.

4. Declaration of the certification decision
   As the final step, the certification body endorses the certification decision made by the Expert Panel II. If the FMU is granted a certificate, then the certification body announces such decision to the publics. In addition, the certification body should also conduct surveillance in the FMU to maintain credibility of the certification decision.

2.2.4. Decision making process

In the LEI system, final decision of certification is made by the Expert Panel II which consists of six experts whose qualification is in production, ecology, and social aspects. As a tool for decision making, LEI uses the Analytic Hierarchy Process (AHP) method (see ***Section 2.3***).

The decision making process in the LEI system involves some activities which can be explained briefly as follows (LEI, 2000):

1. Exposing field assessment results
   The first step is a presentation by the assessors to expose the field assessment results which consist of actual values for each indicator and their justifications. The Expert Panel II uses such field assessment results, inputs from community and recommendation of pre-assessment (see ***Section 2.2.3***) as sources for decision making. All reports are reviewed carefully by the Expert Panel II to verify the field assessment results, particularly related to the value and justification of each indicator.

2. Determining degree of importance of the criteria and indicators
   In the LEI system, each element of the SNPFM hierarchy (indicator, sub-process, process, and criterion) may have different degree of importance with respect to the overall goal of SFM. The degrees of importance, which are represented by weight of each element in the hierarchy, are determined by means of pairwise comparison using the AHP method. The pairwise comparisons are made by the Expert Panel II team for each level of hierarchy, i.e. criteria, process, sub-process, indicator, and intensity scale (norm) levels, by considering which element is more important than others (in the same level of hierarchy) and how important it is. In this case, the nine-point scale (i.e. 1, 2, 3,…,9) from Saaty (1986) is used in the pairwise comparisons to indicate degree of importance of the hierarchy elements (see also ***Section 2.3***). To generate weights from the pairwise comparisons, the Expert Panel II team uses the AHP software called *ExpertChoice*.

3. Determining passing values (minimum requirements)
   To be able to judge whether or not the actual values of each indicator fulfil minimum standard, the Expert Panel II team determines the passing values (minimum requirements) and justifications for each indicator. The passing values provide thresholds for each indicator. Meanwhile, a threshold to judge whether or not the forest management unit pass the certification process is an overall passing value which is calculated from the passing values of each indicator.

4. Determining certification grade
   The Expert Panel II team determines a certification grade based on the overall actual value and the overall passing value as well as understanding of the values and justifications of each indicator. The overall actual value and overall passing value are calculated using the *ExpertChoice* software based on the AHP model developed in the second step. The LEI system uses five grades of certification, namely *gold* (best), *silver*, *bronze*, *copper*, and *zinc* (worst), to indicate achievement level of SFM. These grades are determined using the grading procedure as presented in ***Table 2.2***. A forest management unit should achieve at least *bronze* grade to pass in the certification process and hence can be granted a SFM certificate. In this final stage, the Expert Panel II team also makes some recommendations particularly related to the surveillance activities that should be carried out in the FMU later.

Table 2.2. The grading procedure used to determine the final grade of certification in the LEI system (adapted from: Purbawiyatna, 2002)

Certification grade	Interval of the grade	
	Lower	**Upper**
Gold	P+2U	1.0000
Silver	P+U	(P+2U) – 0.0001
Bronze	P	(P+U) – 0.0001
Cooper	L	P – 0.0001
Zinc	0.0000	L – 0.0001

where: ***P*** is the overall passing value, ***A*** is the overall actual value, ***U***=(1-P)/3 is an interval for upper grades, ***L***=P/2 is an interval for lower grades

2.3. An Overview of the Analytic Hierarchy Process (AHP)

This section presents general concept of the AHP method to provide basic information for the readers to understand the AHP application in the LEI system. Detailed theory and applications of this method can be found in AHP's books such as Saaty (1980), Saaty (1986), Saaty and Vargas (2001), and Forman and Selly (2002).

The Analytic Hierarchy Process (AHP), which is developed by Thomas L. Saaty (see: Saaty, 1980; Saaty and Vargas, 2001), is a multi-criteria decision making (MCDM) method to solve a complex problem by decomposing the problem into a structural hierarchy. In the AHP method, there are three basic principles, namely (Forman and Selly, 2002; Saaty, 1986):

- *decomposition*, which is applied to structure a complex problem into a hierarchy of clusters,
- *comparative judgment*, which is applied to construct pairwise comparisons of all elements in a cluster with respect to the parent of the cluster, and
- *synthesis of priorities*, which is applied to produce global priorities throughout the hierarchy by considering the local priorities of elements in a cluster and the priority of the parent element.

Commonly, there are two AHP models used in practice, namely *relative measurement model* and *rating measurement model*. The relative measurement model is used to prioritize a limited number of alternatives by comparing directly one to another. Meanwhile, the rating measurement model (also called absolute or scoring model) is used to gauge the alternatives against an established scale and not against each other. The later model is used in the LEI system to derive an overall actual value and an overall passing value which are then used to determine the grade of certification.

Based on the AHP principles, the recommended procedure to solve a problem using the AHP method can be explained as follows (based on: Kumar and Ganesh, 1996; Malczewski, 1999; Saaty, 1980; Saaty, 1986; Saaty and Vargas, 2001):

1. Structuring the problem into a hierarchy
   At the first step in using the AHP, one has to structure (decompose) the problem into a hierarchy showing the relationships of overall objective (goal), criteria, sub-criteria and so on, and some alternatives at the bottom of the hierarchy. ***Figure 2.2*** presents a simple example of the AHP hierarchy, which is commonly used in the relative measurement model. Meanwhile, the hierarchy of the LEI system (***Figure 2.1***) is an example of a complex hierarchy for the rating measurement model.

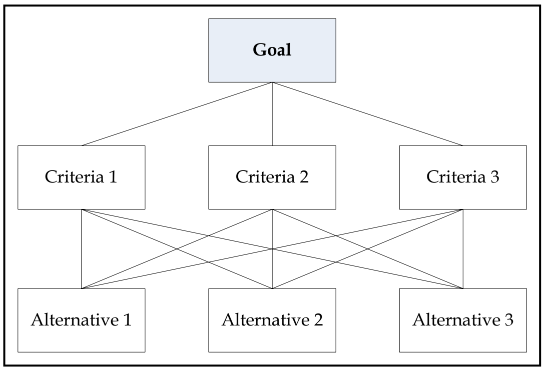


Figure 2.2. An example of the AHP hierarchy with three levels

   As shown in ***Figure 2.1***, the bottom level of the hierarchy represents intensity scales (such as *excellent*, *good*, *fair*, *poor*, and *bad*) to rate the alternatives. In the LEI system, the alternatives are the actual and passing values of each indicator.

2. Comparing the hierarchy elements on a pairwise base
   The pairwise comparisons are basic measurement employed in the AHP method to derive priority vectors for hierarchy levels. At each level of the hierarchy, a decision maker has to make paired comparisons of relative importance of one element to the other ones with respect to every element in the next higher level. The values are entered in pairwise comparison matrices. Commonly, pairwise comparisons are made using verbal judgments according to a fundamental scale as presented in ***Table 2.3***. However, instead of using judgments, the AHP also allows decision makers to use actual measurements from a ratio scale to form a pairwise comparison matrix.

Table 2.3. The fundamental scale of AHP (adapted from: Saaty and Vargas, 2001)

Verbal judgment (if *A* is… as/than *B*)	**Intensity of importance** (then the value to be assigned is…)
Equal importance	1
Moderate importance	3
Strong importance	5
Very strong importance	7
Extreme importance	9
Intermediate preferences between two adjacent judgments	2, 4, 6, 8

The pairwise comparison matrix (PCM) is a reciprocal matrix in which elements under its main diagonal are inverses of the upper elements. For instance, the matrix C below presents a PCM obtained from pairwise comparison of the three criteria (C_1, C_2, and C_3) with respect to the goal (see also ***Figure 2.2***).

$$C = \begin{array}{c} \\ c_1 \\ c_2 \\ c_3 \end{array} \begin{array}{c} \begin{array}{ccc} c_1 & c_2 & c_3 \end{array} \\ \begin{bmatrix} 1 & 3 & 5 \\ 1/3 & 1 & 2 \\ 1/5 & 1/2 & 1 \end{bmatrix} \end{array}$$

If there are n elements to be compared, which will form an n x n PCM, then there will be ***n(n-1)/2*** pairwise comparisons in a PCM. In the LEI system (see ***Figure 2.1***), there would be: 1 PCM consisting of 3 pairwise comparisons for the principle level, 3 PCM consisting of 14 pairwise comparisons for the criteria level, 5 PCM consisting of 5 pairwise comparisons for the process level, 5 PCM consisting of 9 pairwise comparisons for the sub-process level, 17 PCM consisting of 64 pairwise comparisons for the indicator level, and 57 PCM consisting of 570 pairwise comparisons for the norms (intensity scale).

For each pairwise comparison matrix (PCM), one has to generate priority or weight of the elements (e.g. alternatives, criteria) using the eigenvector method. Based on this method, the priority vector for each PCM can be obtained by normalizing the principal eigenvector which corresponds to the principal eigenvalue of a PCM. The detailed procedures and examples of calculating the priority vector as well as the procedure to check inconsistency of a PCM can be found in Saaty (1980; Saaty, 1986). In practice, these processes can easily be done by using an AHP software such as *ExpertChoice*.

3. Aggregating all the priority vectors

   The final step is to aggregate the priority (weight) vectors of each level obtained in the second step, to produce overall weights. This is done by means of a sequence multiplication of the weight vectors at each level of the hierarchy. The overall weights represent rating of alternatives with respect to the overall goal. The overall score R_i of the i-th alternative is the total sum of its ratings at each of the levels which is computed as follows (Malczewski, 1999):

$$R_i = \sum_k w_k r_{ik} \tag{2.1}$$

   where: w_k is the vector of priorities associated with the k-th element of the hierarchy and r_{ik} is the vector of priorities derived from comparing alternatives on each criterion. In the LEI system (see ***Figure 2.1***), this process will be repeated for all levels of hierarchy to produce absolute weights in all levels of the hierarchy. The absolute weights in the indicator level can be used to calculate the overall actual value and the overall passing value as weighted sum of actual and passing values of the indicators. These overall values in turn are used to determine grades of certification.

2.4. Foundations of Fuzzy Logic

This section presents briefly some basic concepts of fuzzy logic to give foundations for the readers to follow the idea of this study. For further information about fuzzy logic theory, the interested readers may refer to advanced textbooks such as Klir and Yuan (1995), Zimmermann (1985), Lootsma (1997), Berkan and Trubatch (1997), and Tanaka (1996).

2.4.1. What is fuzzy logic?

Fuzzy logic is an extension of the classical (Boolean) logic that can be used to handle mathematically the vagueness of human linguistics and thinking (Tanaka, 1996). In other words, it provides a logical system to formalize approximate reasoning (Zadeh, 1994). Actually, the foundation of fuzzy logic is the fuzzy set theory that was initially introduced by Zadeh (1965). However, currently there is a growing tendency to use fuzzy logic term as almost synonymous with fuzzy set theory (Zadeh, 1994).

The fundamental difference between Boolean logic and fuzzy logic is the concept of truth values. In Boolean logic, truth values of a proposition are either completely false or true which correspond to values 0 or 1. In fuzzy logic truth is a matter of degree, hence the truth values range continuously between 0 and 1. The concept of partial truth as addressed by fuzzy logic is more appropriate to represent the perception of truth in the real world than that of Boolean logic. Indeed, in our daily life almost all the propositions, particularly related to human reasoning, are within some proximity of the absolutely true or false (Berkan and Trubatch, 1997; Klir and Yuan, 1995). For instance, words such as *beautiful* and *old* would have different degree of truth depending on the person who judges them, in which most probably one will judge them by using vague terms such as *fairly beautiful* or *somewhat old*. In this case, fuzzy logic can handle such vagueness mathematically (Tanaka, 1996).

In summary, fuzzy logic provides a method for reasoning with fuzzy propositions that have partial truth values as commonly found in natural language. In fuzzy logic, logical inference can be made by combining some simple statements using linguistic operators (e.g. *if-then*), such as in "*If concentration of suspended soil is low then water quality is good*". Using fuzzy logic, one can build a system (called *fuzzy rule-base system*) that embeds human knowledge to perform approximate reasoning in a realistic manner (Berkan and Trubatch, 1997).

2.4.2. Fuzzy sets

A fuzzy set is a class of objects with a continuum of membership degrees. It is characterized by a membership function that assigns degree ranging between zero and one (Zadeh, 1965). Mathematically, a fuzzy set A in a universe of discourse X is characterized by a membership function μ_A that can be defined as follows (Klir and Yuan, 1995):

$$\mu_A : X \to [0,1] \tag{2.2}$$

It is obvious that if the value of $\mu_A(x)$ is closer to 1 then the degree of x belonging to the fuzzy set A become higher (Tanaka, 1996).

In general, there are two ways of expressing a fuzzy set, namely (Tanaka, 1996):

- When the universe of discourse X is discrete, a fuzzy set A can be expressed as:

$$A = \sum_{i=1}^{n} \mu_A(x_i)/x_i \tag{2.3}$$

- When the universe of discourse X is continuous, a fuzzy set A can be expressed as:

$$A = \int_x \mu_A(x_i)/x_i \tag{2.4}$$

The symbol / in (2.3) and (2.4) is a separator between an element of the universe of discourse (in the right) and the membership degree (in the left).

2.4.3. Operations of fuzzy sets

There are three fundamental operations of fuzzy sets, namely: complement, union, and intersection, which can be defined as follows (Klir and Yuan, 1995; Tanaka, 1996):

- *Complement* of fuzzy set A is a fuzzy set that is defined by the membership function:

$$\mu_{\bar{A}}(x) = 1 - \mu_A(x), \text{ for all } x \in X \tag{2.5}$$

- *Union* of two fuzzy sets A and B is a fuzzy set that is defined by the membership function:

$$\mu_{A \cup B}(x) = \max[\mu_A(x), \mu_B(x)], \text{ for all } x \in X \tag{2.6}$$

- *Intersection* of two fuzzy sets A and B is a fuzzy set that is defined by the membership function:

$$\mu_{A \cap B}(x) = \min[\mu_A(x), \mu_B(x)], \text{ for all } x \in X \tag{2.7}$$

2.4.4. Linguistic variables

The concept of a linguistic variable plays important role particularly in fuzzy logic. A linguistic variable is a variable whose values are expressed in words or sentences in natural language (Zimmermann, 1985). The linguistic variable is characterized by four items: name, base variable, linguistic value, and membership functions (Cornelissen et al., 2001; Klir and Yuan, 1995). ***Figure* 2.3** illustrates an example of a linguistic variable. In this example, the name of the linguistic variable is *Size of protected area* which is defined by *the proportion of protected area* as the base variable. The linguistic values are *small*, *medium* and *large*. One might define *small* as "size of protected area below about 30% of the total area", *medium* as "size of protected area close to 50% of the total area", and *large* as "size of protected area above about 70% of the total area". Each linguistic value is characterized by a fuzzy set whose membership function is shown in ***Figure* 2.3.**

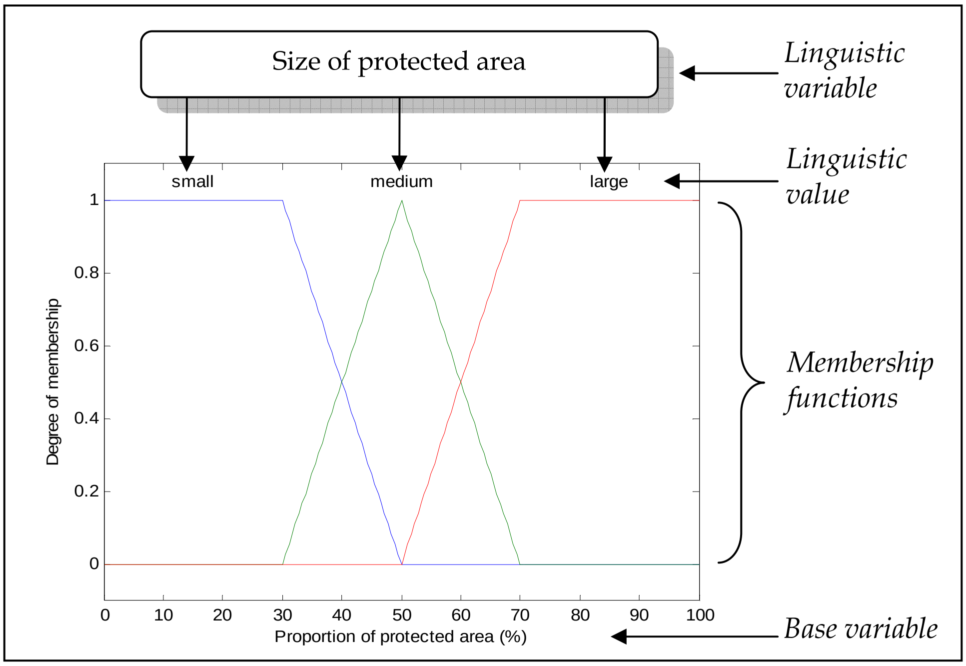


Figure 2.3. An illustration of a linguistic variable (based on: Cornelissen et al., 2001; Klir and Yuan, 1995)

2.4.5. Fuzzy rule-based system

As used in this study, the term *fuzzy rule-based system* refers to the application of fuzzy logic for reasoning with fuzzy propositions (statements) in order to infer a conclusion. In a fuzzy rule-based system, knowledge for reasoning is expressed in an *if-then* statement which consists of two parts, i.e. an antecedent and a consequent. The antecedent part stating conditions on the input variables, which may consist of a single fuzzy statement or a series of fuzzy statements that are combined using logical operators such as AND and OR. The consequent part describing the corresponding value of the output variables, which is generated by an implication operator such as MIN or MAX operator (Adriaenssens et al., 2004; Berkan and Trubatch, 1997).

Currently there are two commonly used fuzzy inference methods that can be implemented in a fuzzy rule-based system, namely Mamdani method and Takagi-Sugeno method. Generally, both methods are similar to each other in many aspects of fuzzy inference. The main difference is that in Mamdani method both antecedent and consequent parts are fuzzy statements, whereas in Takagi-Sugeno method the consequent part is a linear function of the input and the output variables (Adriaenssens et al., 2004; MathWorks, 2002; Tanaka, 1996). As pointed out by Adriaenssens et al. (2004), the Mamdani method seems to be an appropriate fuzzy inference method that can be used for the assessment of ecosystem management, such as SFM assessment in the context of this study, because both antecedent and consequent part are usually expressed by the experts in fuzzy statements using linguistic values such as *bad*, *fair* or *excellent*.

In the fuzzy rule based system, mechanism of fuzzy reasoning (as implemented in Mamdani method) is based on the generalized modus ponens (GMP) which has a typical form as follows (Tanaka, 1996):

premise 1 (*rule*):	IF x is A THEN y is B
premise 2 (*data*):	x is A′
consequence:	y is B′

The reasoning using GMP is considered as the most suitable inference mechanism in expressing human knowledge using a series of *if-then rules* (Berkan and Trubatch, 1997). For instance, in the previous example (see ***Section 2.3.4***), the reasoning could be expressed as follows:

premise 1 (*rule*):	IF proportion of the protected area is *large* THEN the stability of forest ecosystem is *good*
premise 2 (*data*):	the proportion of protected area is *about 70%*
consequence:	the stability of forest ecosystem will be *good* accordingly

In Mamdani method, the reasoning process consists of three main steps, namely: 1) measure adaptability of the premises for a given input, 2) infer conclusions of each rule, and 3) aggregate the individual conclusions to obtain an overall conclusion (Tanaka, 1996). To illustrate the process, let us consider the following rules having two linguistic variables (x and y) in the premise part and one variable (z) in the consequence part:

- Rule 1: IF x is A_1 AND y is B_1 THEN z is C_1
- Rule 2: IF x is A_2 AND y is B_2 THEN z is C_2

Suppose that x_0 and y_0 are inputs for the x and y variables, respectively. The reasoning process for these inputs using those rules are illustrated in ***Figure 2.4*** and explained as follows:

1) The adaptability (W_i) of each rule is computed by using minimum (MIN) operation as follows:
   - Adaptability of Rule 1: $W_1 = \min\left[\mu_{A_1}(x_0), \mu_{B_1}(y_0)\right]$ (2.8)
   - Adaptability of Rule 2: $W_2 = \min\left[\mu_{A_2}(x_0), \mu_{B_2}(y_0)\right]$ (2.9)
2) The individual conclusions of each rule are obtained by applying the adaptability of each rule to the fuzzy sets in the consequence part as follows:
   - Conclusion of Rule 1: $\mu_{C_1'}(x_0) = \min\left[W_1, \mu_{C_1}(z)\right]$ (2.10)
   - Conclusion of Rule 2: $\mu_{C_2'}(x_0) = \min\left[W_2, \mu_{C_2}(z)\right]$ (2.11)
3) An overall conclusion is obtained by aggregating the individual conclusions using maximum (MAX) operation as follows:
   - Overall conclusion: $\mu_C(z) = \mu_{C_1'}(z) \vee \mu_{C_2'}(z)$ (2.12)

   In practical applications, usually the fuzzy set of overall conclusion ($\mu_C(z)$) is converted into a crisp value using defuzzification method such as center of gravity (centroid).

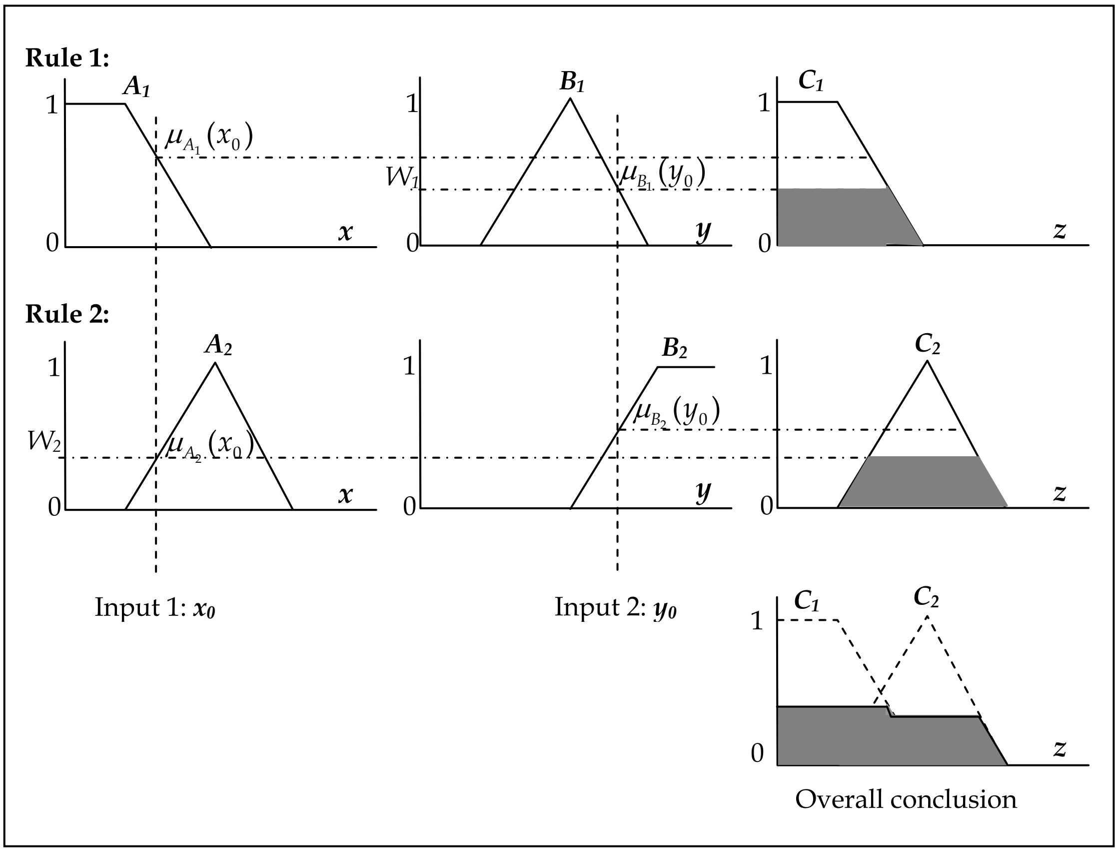


Figure 2.4. Reasoning process in Mamdani method (adapted from: Tanaka, 1996)

Chapter 3

Research Method

3.1. Study Area

In general, this study concerns with decision making issues in forest certification system developed by LEI (Indonesian Ecolabelling Institute) to assess sustainable natural production forest management (SNPFM) in Indonesia. However, in order to test applicability of the proposed method in a real decision making process, this study used the data obtained from forest certification process in the Labanan concession.

The Labanan concession (formally called PT. Inhutani I Unit Labanan) is located in Berau district, East Kalimantan, Indonesia. Geographically, it is located between latitude of 02°10′ and 01°45′ N and longitude of 116°55′ and 117°20′ E (see ***Figure 3.1***). Since 1976, the concession has been managing natural production forests with a total area of 83240 hectares. In 1999, this concession was pointed by the government as a research area of Berau Forest Management Project (BFMP), which was a cooperation program between Indonesia government and European Union to promote SFM (MAL, 2002).

The certification process in the Labanan concession has been carried out by two certification bodies, namely PT. Mutuagung Lestari which used LEI system and Smartwood which used FSC (Forest Stewardship Council) system, through a joint certification program in 2000. Based on their assessment, in 2001 LEI declared that the Labanan concession has passed the certification process and hence eligible to be granted an SFM certificate (MAL, 2002).

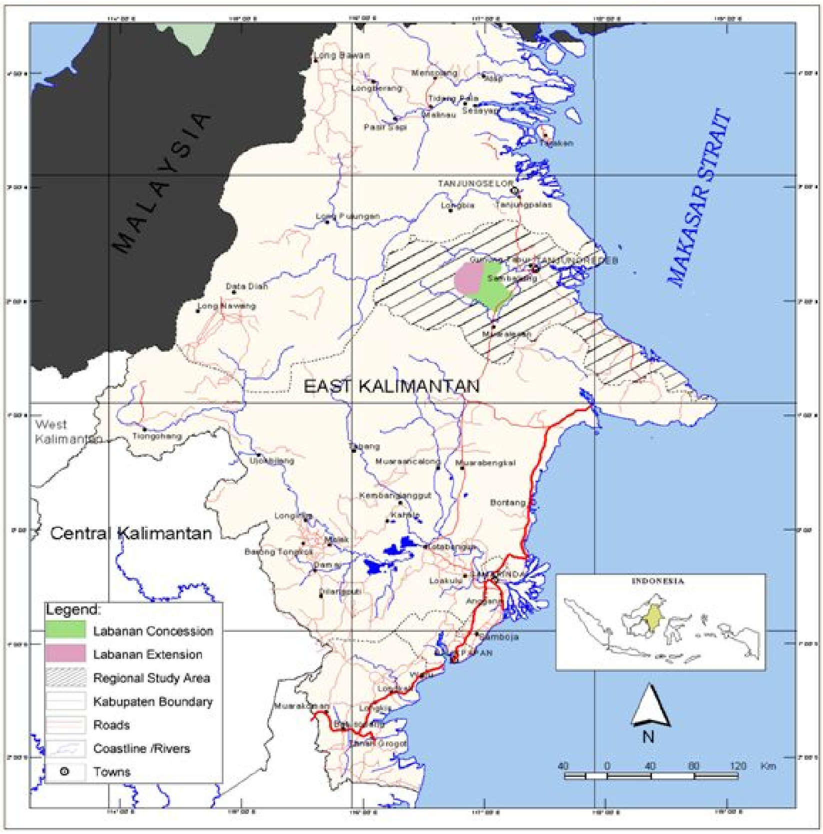


Figure 3.1. Labanan concession area (Steenis, 1999)

3.2. Methods

This study was carried out based on the methods as depicted in ***Figure 3.2.*** In this case, the expert knowledge and the LEI's C&I set provided data to derive rule base. Using this rule base, the fuzzy rule-based (FRB) model can be developed through four main steps: normalization, fuzzification, fuzzy inference, and defuzzification. The results were FRB-1 model which was tested using the real assessment data and FRB-2 model which was tested using hypothetical data. To analyze robustness of the FRB model, sensitivity analysis was carried out by adopting different shapes of membership functions and changing the values of some important indicators. The results obtained from the FRB model were compared to those obtained from the existing method (AHP). Furthermore, simulations were performed to simulate some possible SFM assessment using the FRB model. In details, the methods are further explained in the following sections.

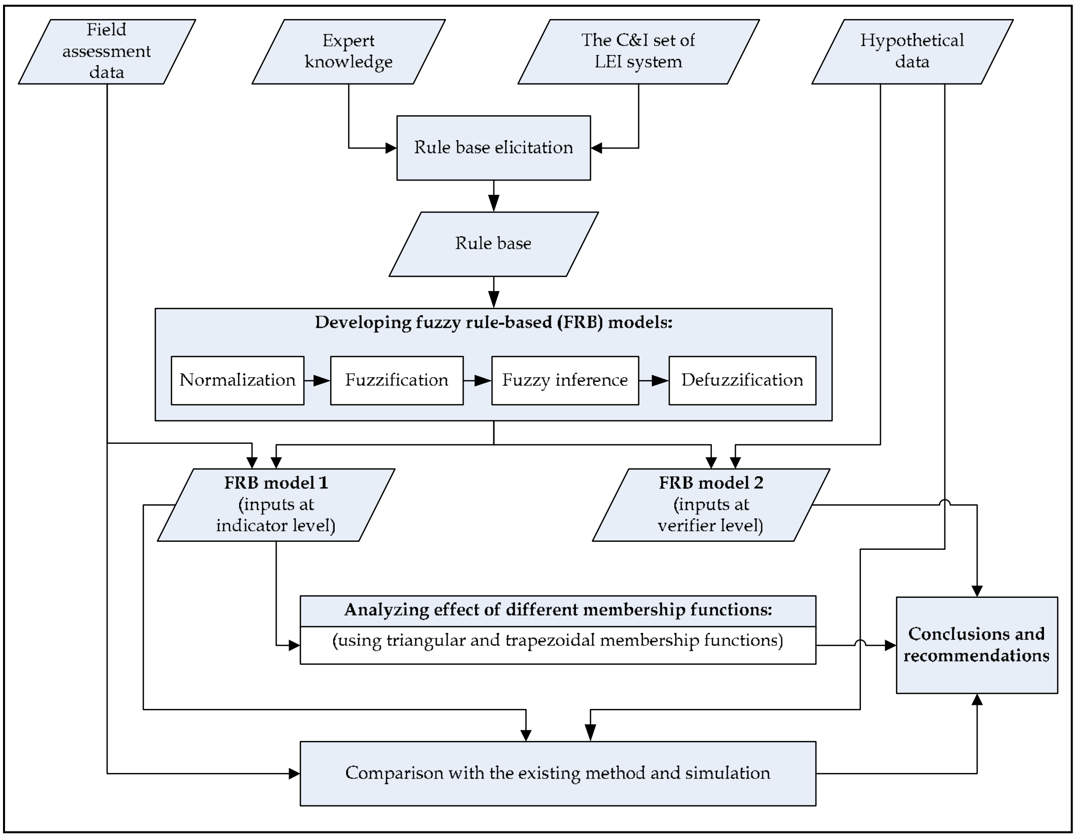


Figure 3.2. The research method

3.2.1. Data collection

There were three main data sources for this study, namely: expert knowledge, assessment data of certification process in the Labanan concession, and relevant documents of the LEI system.

The expert knowledge was used as primary data to develop the rule base for assessing ecological sustainability of SFM. The experts came from the Faculty of Forestry of Bogor Agricultural University (IPB), Indonesia. They have been involved in developing the criteria and indicators of the LEI system and they are still involved in forest certification activities in Indonesia. Accordingly, some intensive discussions with the experts were carried out to get a better understanding of the ecological criteria and indicators, particularly related to their order of importance in assessing sustainability, the most relevant verifiers to assess ecological indicators, and the logical thinking on how to aggregate linguistically the various components of the criteria and indicators in order to determine an overall value indicating achievement of ecological sustainability of SFM.

The assessment data of certification process in Labanan concession were obtained from LEI. These data consist of: 1) the values of each indicator both the actual performances (as judged by the assessor in the field) as well as the passing performances (as judged by the Expert Panel II) which were documented in MAL (2001; MAL, 2002), and 2) the pairwise comparison matrices for each level of the hierarchy as used by LEI in decision making process using the AHP method (see ***Appendix E***).

Some relevant documents were also obtained from LEI. These documents included the LEI's guidelines of certification system for sustainable natural production forests management (see LEI, 2000), the report of field assessment results in Labanan concession (see MAL, 2001), and the report of performance evaluation and the Expert Panel II recommendations on forest certification in Labanan concession (see MAL, 2002).

To get a better understanding on how the certification process has been done by the certification bodies, a field visit to the Labanan concession area has also been carried out during the fieldwork. Discussions with the local authorities of the Labanan concession were carried out during the fieldwork to explore their experiences in the certification process as well as their current activities in managing natural production forest in this concession.

3.2.2. Rule base elicitation

Usually, in an SFM assessment the experts use their own knowledge and logical thinking on how to determine a value for each verifier and indicator and then aggregate them linguistically over the hierarchy to come up with the final decision of certification. In the LEI system, the aggregation is done using weights. In this study, we express the expert knowledge for aggregation in terms of fuzzy rules. The fuzzy rules consist of a series of linguistic statements representing the expert knowledge used in assessing SFM, which can be expressed in several *if-then* statements, for instance: "IF the size of damage in the protected area is *small* AND the degree of damage is *low* AND the efforts to control the damages are *adequate* THEN the intensity of damage in the protected area is *low*" (see also ***Section 2.4***)

In this study, the rule base elicitation was focused to extract the expert knowledge on how to assess ecological sustainability of SFM using the LEI system (see ***Figure 1.1***). The number of rules would depend on the number of input variables and their linguistic values. Mathematically, if there are ***n*** input variables and ***L*** linguistic values then the total number of rules would be $R = L^n$ (Phillis and Andriantiatsaholiniaina, 2001). For instance, the total number of rules for the area management (see ***Figure 1.1***) would be $R = 5^4 = 625$ rules because there are 4 indicators (e.g. E1.1, E1.2, E1.3, E1.4) and 5 linguistic values (i.e. *excellent*, *good*, *fair*, *poor*, and *bad*). It would not be possible to derive directly all rules from the experts due to huge amount of the input variables and limited time of the experts. In this study, therefore, the rules have been derived using indirect approach in which only the main guidelines and logical thinking have been discussed intensively with the experts. In this case, the experts argued that an intuitive way to derive rules is by considering the order of importance of the ecological verifiers, indicators and criteria, and then relate them to the actual context of forest management in the Labanan concession. Hence, the reasoning and major backbone arguments from the experts have been analyzed as foundations to derive the complete rule base. In addition, the available documents of the LEI system were also used as additional sources to derive the rules, particularly for aggregating the verifiers to indicator level.

3.2.3. Development of the fuzzy rule-based model

As a core of this study, the fuzzy rule-based models have been developed as alternative tools for determining overall actual and passing performances of ecological sustainability of SFM. There were two types of the fuzzy rule-based models developed in this study, namely:

1). ***Fuzzy rule-based model 1 (FRB-1)***, which provided a model for assessing ecological sustainability of SFM using inputs starting at the indicator level and then aggregate them up to the principle level. This model was similar to the existing model in the LEI system in which the inputs are values of each indicator, but this model used fuzzy rule-based approach as a means to aggregate linguistically those values instead of using numerical aggregation as implemented in the existing method. ***Figure 3.3*** presents the architecture of the FRB-1 model.

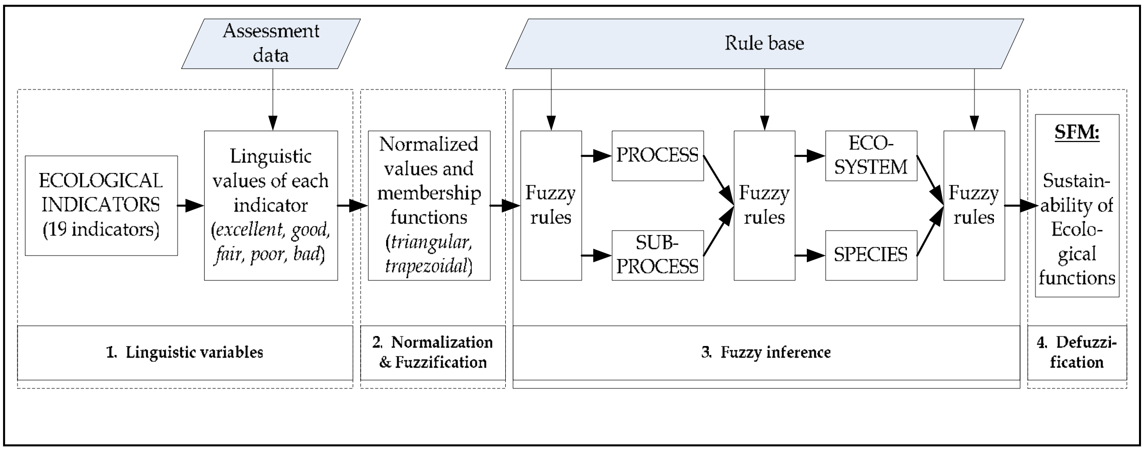


Figure 3.3. The architecture of the fuzzy rule-based model 1 (FRB-1)

2). ***Fuzzy rule-based model 2 (FRB-2)***, which is similar to the FRB-1 but using the inputs starting at the verifier level and then aggregate them up to the principle level. The purpose of developing FRB-2 model was to provide an alternative tool for the decision makers to integrate and aggregate various values of each verifier directly into one framework of decision making. It was assumed that the assessors would be able to determine values of each verifier and then put them into the FRB-2 model to get directly the final decision of certification. ***Figure 3.4*** presents the architecture of the FRB-2 model.

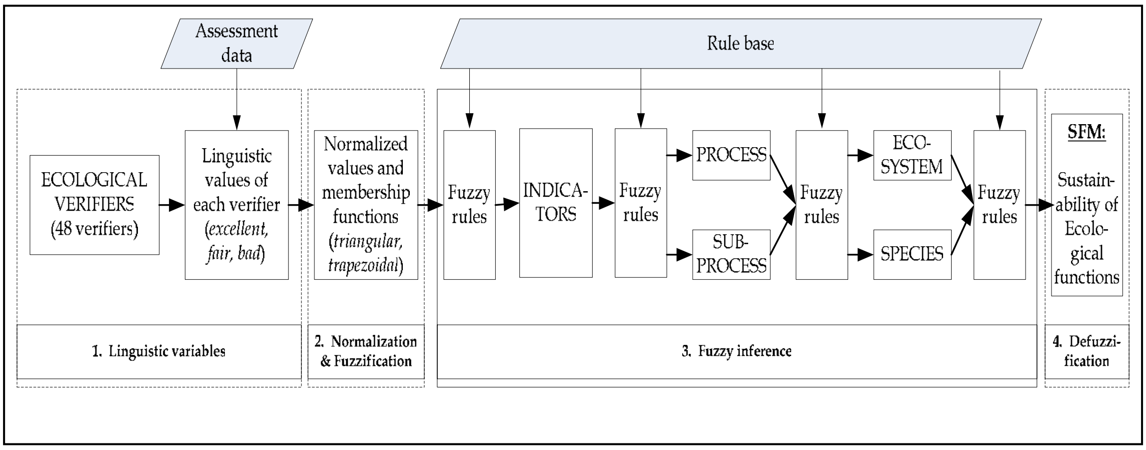


Figure 3.4. The architecture of the fuzzy rule-based model 2 (FRB-2)

In details, the methods that were used to develop each FRB model can be explained as follows (based on: Andriantiatsaholiniaina et al., 2004; Cornelissen et al., 2001):

1). Defining linguistic variables

All elements in the hierarchy of ecological sustainability (as depicted in ***Figure 1.1***), which consists of 1 principle, 2 criteria, 4 processes, 4 sub-processes, 19 indicators, and 48 selected verifiers, are linguistic variables. There were three linguistic values used in each variable at the verifier level (i.e. *excellent*, *fair* and *bad*) and there were five linguistic values for the other levels (i.e. *excellent*, *good*, *fair*, *poor* and *bad*). For the principle level such linguistic values were considered directly as the grades of certification, namely: *gold* (the best), *silver, bronze, copper* and *zinc* (the worst). Description of the linguistic variables as well as their linguistic values for the indicator level is presented in ***Appendix A***, and for the verifier level is presented in ***Appendix C***. It is important to note here that the description of each linguistic value of each verifier does not exist in the LEI system, but it was formulated for the purpose of this study (particularly for the FRB-2 model) based on the available information from the documents and the experts. ***Table 3.1*** summarizes the names and values of each linguistic variable that was used in the FRB-1 and the FRB-2 models.

Table 3.1. Linguistic values used in the FRB-1 and FRB-2 models

Linguistic variable	Linguistic value	FRB model
Ecological sustainability (ECO)	*Gold, silver, bronze, copper, zinc*	FRB-1 & FRB-2
1. Stability of ecosystem (SE)	*Excellent, good, fair, poor, bad*	FRB-1 & FRB-2
1.1. Area management (AM-1)	*Excellent, good, fair, poor, bad*	FRB-1 & FRB-2
1.2. Forest management (FM-1)	*Excellent, good, fair, poor, bad*	FRB-1 & FRB-2
1.2.1. Production management (PM-1)	*Excellent, good, fair, poor, bad*	FRB-1 & FRB-2
1.2.2. Environmental management (EM-1)	*Excellent, good, fair, poor, bad*	FRB-1 & FRB-2
2. Survival of endangered species (SS)	*Excellent, good, fair, poor, bad*	FRB-1 & FRB-2
2.1. Area management (AM-2)	*Excellent, good, fair, poor, bad*	FRB-1 & FRB-2
2.2. Forest management (FM-2)	*Excellent, good, fair, poor, bad*	FRB-1 & FRB-2
2.2.1. Production management (PM-2)	*Excellent, good, fair, poor, bad*	FRB-1 & FRB-2
2.2.2. Social management (SM-2)	*Excellent, good, fair, poor, bad*	FRB-1 & FRB-2
3. Indicators level (19 indicators)	*Excellent, good, fair, poor, bad*	FRB-1 & FRB-2
4. Verifier level (48 selected verifiers)	*Excellent, fair, bad*	FRB-2

2). *Normalization*

Normalization is a way to obtain a common scale to allow aggregation and to facilitate fuzzy computations (Phillis and Andriantiatsaholiniaina, 2001). In this study, the input values for each linguistic variable in the indicator level (for FRB-1) or in the verifier level (for FRB-2) were expressed using linguistic terms (e.g. *excellent*, *fair*, or *bad*). To allow computations, the linguistic values were converted into normalized crisp values derived from the pairwise comparison matrices of the AHP method (see ***Appendix E***). All computations related to deriving the crisp values were done using *ExpertChoice* software. ***Table 3.2*** provides the normalized crisp values used to express verbal judgment for each indicator.

Table 3.2. The normalized crisp values used as inputs for indicators

Indicator	Normalized value				
	Excellent	Good	Fair	Poor	Bad
E1.1	1.000	0.577	0.325	0.129	0.079
E1.2	1.000	0.568	0.303	0.160	0.093
E1.3	1.000	0.436	0.239	0.128	0.075
E1.4	1.000	0.689	0.405	0.265	0.132
E1.5	1.000	0.571	0.310	0.155	0.082
E1.6	1.000	0.571	0.308	0.170	0.076
E1.7	1.000	0.568	0.303	0.160	0.093
E1.8	1.000	0.603	0.242	0.134	0.080
E1.9	1.000	0.603	0.242	0.134	0.080
E1.10	1.000	0.603	0.242	0.134	0.080
E1.11	1.000	0.603	0.242	0.134	0.080
E2.1	1.000	0.577	0.325	0.129	0.079
E2.2	1.000	0.568	0.303	0.160	0.093
E2.3	1.000	0.85	0.416	0.215	0.123
E2.4	1.000	0.689	0.405	0.265	0.132
E2.5	1.000	0.571	0.310	0.155	0.082
E2.6	1.000	0.436	0.239	0.128	0.075
E2.7	1.000	0.603	0.242	0.134	0.080
E2.8	1.000	0.603	0.242	0.134	0.080
Minimum	1.000	0.436	0.239	0.128	0.075
Average	1.000	0.850	0.416	0.265	0.132
Maximum	1.000	0.088	0.060	0.043	0.019
St.dev.	0.000	0.594	0.297	0.159	0.089

3). *Fuzzification*

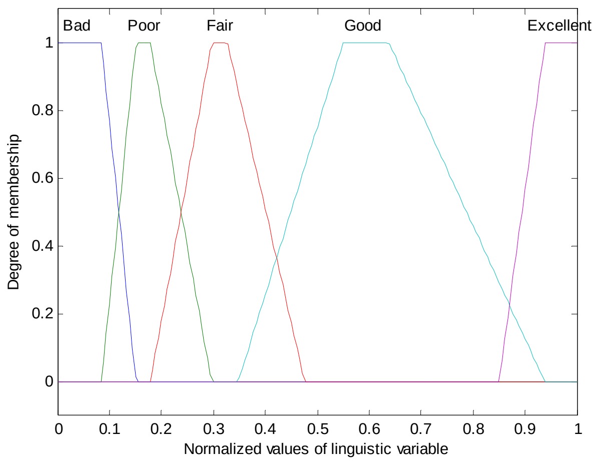
The FRB model works with linguistic values such as *excellent*, *fair*, or *poor*. Membership functions of these linguistic values are needed to determine membership degree of a crisp input. Actually, there is no fixed rule to construct appropriate membership functions for linguistic values. In this study, we used trapezoidal shapes of membership functions which parameters were derived from statistics (minimum, maximum, mean, and standard deviation) of the crisp values assigned to a linguistic value as presented in ***Table 3.2*** in order to provide reasonable results. The trapezoidal membership functions were chosen because they seemed to be more appropriate for representing membership degree of the linguistic values which have a certain range of the normalized crisp values. Besides, they are also commonly used in practical applications (Berkan and Trubatch, 1997; Pedrycz, 1994). In general, a trapezoidal membership function can be defined as follows:

$$\mu(x) = \begin{cases} 0 & , \quad x \le a \\ \dfrac{x-a}{b-a} & , \quad a \le x \le b \\ 1 & , \quad b \le x \le c \\ \dfrac{d-x}{d-c} & , \quad c \le x \le d \\ 0 & , \quad d \le x \end{cases} \qquad (3.1)$$

In this study, the four parameters (*a*, *b*, *c*, and *d*) of membership function for each linguistic value (*excellent*, *good*, *fair*, *poor*, and *bad*) of the FRB-1 and the FRB-2 models were derived using statistical approach as follows:

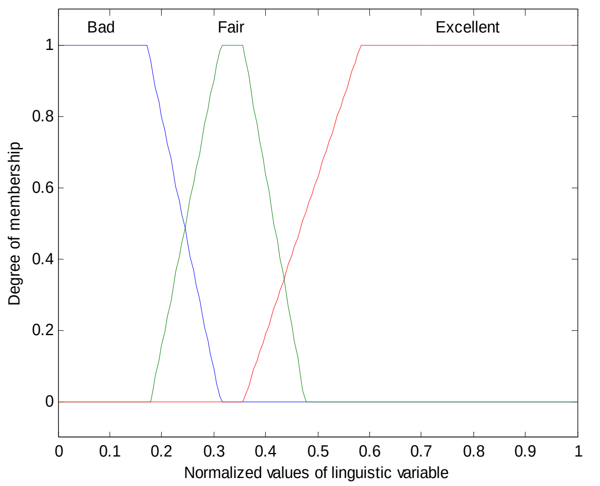
$$a = Min - (c).Stdev; \quad b = Mean - (c).Stdev;$$
$$c = Mean + (c).Stdev; \quad d = Max + (c).Stdev \qquad (3.2)$$

where: *Min*, *Mean*, *Max*, *Stdev* are the minimum, average, maximum, and standard deviation of the normalized crisp values of each linguistic value (***Table 3.2***), and *c* is a constant which was determined experimentally; it was found that *c*=1 (for *a* and *d*) and *c*=0.5 (for *b* and *c*) provided reasonable results. It is important to note here that for membership functions of the three linguistic values (*excellent*, *fair*, *poor*) in the FRB-2 model, the parameters were derived based on statistics calculated by combining the crisp values of: *excellent* and *good*, *fair*, *poor* and *bad*. It was assumed that the expert preferences about linguistic values in the verifier level were the same with those in the indicator level. Some adjustments were made by ensuring: $c_i \le a_{i+1}$ and $d_i \le b_{i+1}$, to avoid superfluous overlapping between two consecutive linguistic values. Based on this approach, the most appropriate trapezoidal membership functions, which were used for all the linguistic variables at the indicator level up to the principle level in both FRB-1 and FRB-2 models, are depicted in ***Figure 3.5***. In addition, ***Figure 3.6*** depicts the trapezoidal membership functions that were used at the verifier level in the FRB-2 model.



where: *Bad*=[0 0 0.085 0.151]; *Poor*=[0.085 0.151 0.179 0.297]; *Fair*=[0.179 0.297 0.327 0.476]; *Good*=[0.348 0.55 0.638 0.938]; *Excellent*=[0.85 0.938 1 1]

Figure 3.5.
The trapezoidal membership functions used in FRB-1 and FRB-2 model for the linguistic variables at the indicator level up to the principle level



where: Bad=[0 0 0.172 0.313]; *Fair*=[0.179 0.313 0.357 0.476]; *Excellent*=[0.357 0.583 1 1]

Figure 3.6.
The trapezoidal membership functions used in FRB-2 model for the linguistic variables at the verifier level

4). Fuzzy inference

Fuzzy inference is a process of deriving fuzzy conclusions from fuzzy premises based on a set of fuzzy rules, which consists of an implication process and an aggregation process. The implication process derives an individual fuzzy conclusion for each rule, whereas the aggregation process derives an overall fuzzy conclusion based on the individual fuzzy conclusion for the entire fuzzy rule base (Cornelissen et al., 2001). In this study, fuzzy inferences for both FRB-1 and FRB-2 models were performed based on the Mamdani's inference method which uses minimum (MIN) operator in the implication process and maximum (MAX) operator in the aggregation process. The implication process using MIN-operator was considered more appropriate because the FRB models developed in this study would not allow compensations as it happens in the AHP method. ***Figure 3.7*** provides an illustration of fuzzy inference to derive conclusions of value of the linguistic variable *production management* based on the linguistic values of *indicator E2.5* and *indicator E2.6*. By using this illustration, the fuzzy inference process can be explained as follows:

- Suppose, x_1=0.3 and x_2=0.1 are the crisp values for the indicator E2.6 and the indicator E2.5, respectively. For simplicity, the triangular membership functions (as used in the FRB-1c model, see ***Figure 3.9b***) are used to fuzzify the x_1 into *fair* with membership degree 0.2 and *poor* with membership degree 0.8, and the x_2 is fuzzified into *poor* with membership degree 0.4 and *bad* with membership degree 0.6.
- Then, the fuzzified values are used by FRB model to activate appropriate rules and perform fuzzy inference (i.e. implication process using MIN operator) as follows:
  - **Rule 1**: IF Indicator E2.6 is 0.2 *fair* AND Indicator E2.5 is 0.4 *poor* THEN Production Management is *poor* with membership degree 0.2 (=min{0.2, 0.4})
  - **Rule 2**: IF Indicator E2.6 is 0.2 *fair* AND Indicator E2.5 is 0.6 *bad* THEN Production Management is *poor* with membership degree 0.2 (=min{0.2, 0.6})
  - **Rule 3**: IF Indicator E2.6 is 0.8 *poor* AND Indicator E2.5 is 0.4 *poor* THEN Production Management is *poor* with membership degree 0.4 (=min{0.8, 0.4})
  - **Rule 4**: IF Indicator E2.6 is 0.8 *poor* AND Indicator E2.5 is 0.6 *bad* THEN Production Management is *bad* with membership degree 0.6 (=min{0.8, 0.6})
- The individual fuzzy conclusions of each rule are aggregated using MAX operator to derive an overall fuzzy conclusion C using defuzzification method (see ***Step 4*** below).

Using similar approach as explained above, the fuzzy inference processes were carried out simultaneously from the lower level of the hierarchy (i.e. the indicator level for FRB-1 or the verifier level for FRB-2) up to the principle level.

5). Defuzzification

Defuzzification refers to the process of converting fuzzy numbers, which are obtained from the fuzzy inference process, into a crisp value. In this study, main purpose of the defuzzification was to obtain an overall value indicating achievement of ecological sustainability of SFM and its corresponding certification grade (*gold, silver, bronze, cooper,* or *zinc*) based on the FRB approach. The defuzzification process was performed using the *center of gravity (centroid) method*, which is the most widely used defuzzification method (Berkan and Trubatch, 1997; Cornelissen et al., 2001; MathWorks, 2002; Phillis and Andriantiatsaholiniaina, 2001), as described below:

- The output of aggregation process in the fuzzy inference was a fuzzy set *C* whose membership degrees are defined by the MAX operator:

  $$\mu_C(z) = \max_{r=1,2,\ldots} \mu_{C,r}(z) \qquad (3.3)$$

  where: μ_C is the membership function of the fuzzy set *C* and $\mu_{C,r}$ is the membership function of each individual fuzzy conclusion (see ***Figure 3.8***).
- The final crisp value (y_C) was given by the *center of gravity* formula as follows (Berkan and Trubatch, 1997; Klir and Yuan, 1995):

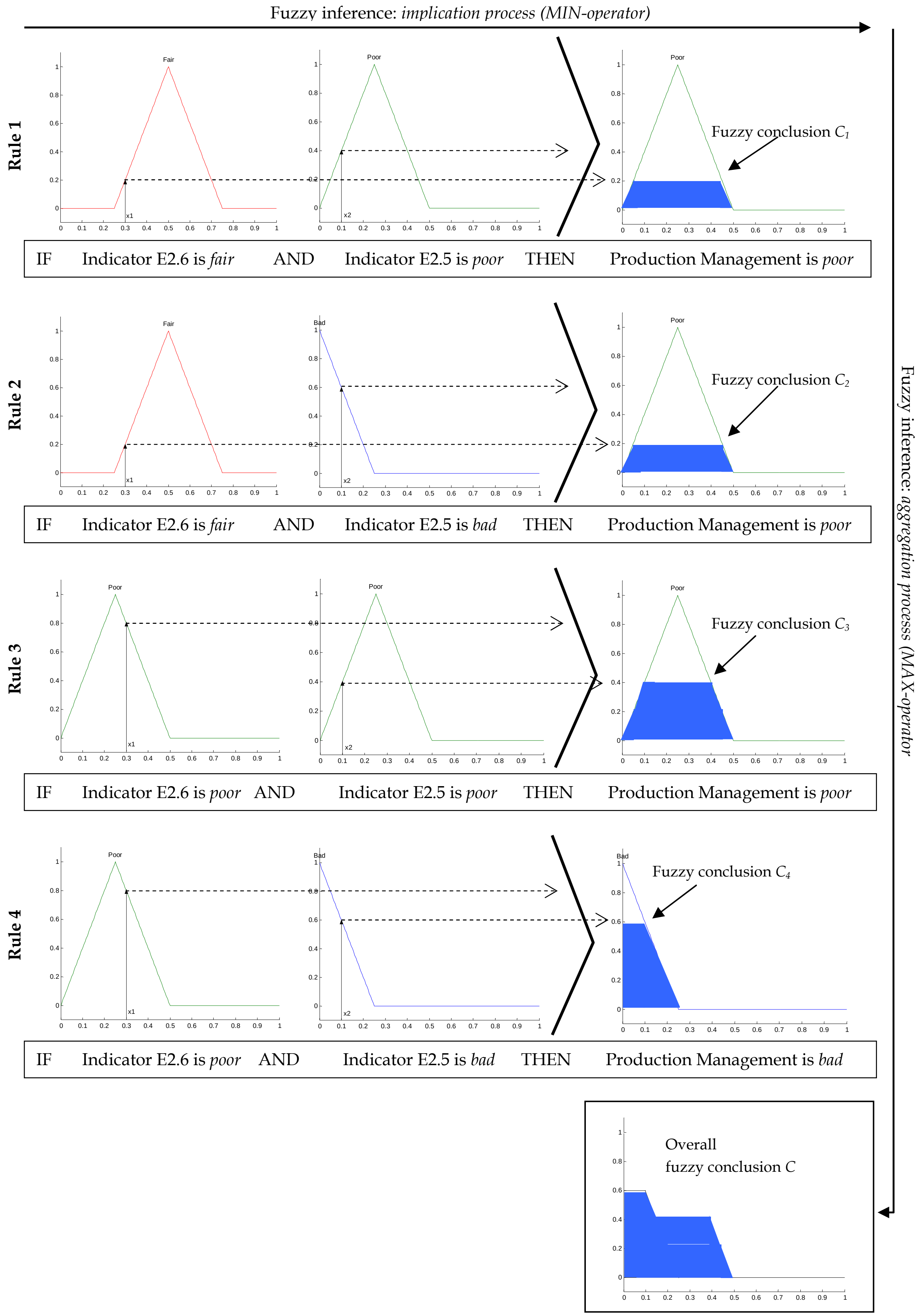


Figure 3.7. An illustration of fuzzy inference process (based on: Cornelissen et al., 2001)

$$y_C = \frac{\int_0^1 z\mu_C(z)\,\mathrm{dz}}{\int_0^1 \mu_C(z)\,\mathrm{dz}} \tag{3.4}$$

which can be approximated using discrete values as follows:

$$y_C \cong \frac{\sum_j z_j \mu_C(z)}{\sum_j \mu_C(z)} \tag{3.5}$$

As an illustration of the defuzzification process, let us consider the example from the fuzzy inference above as depicted below:

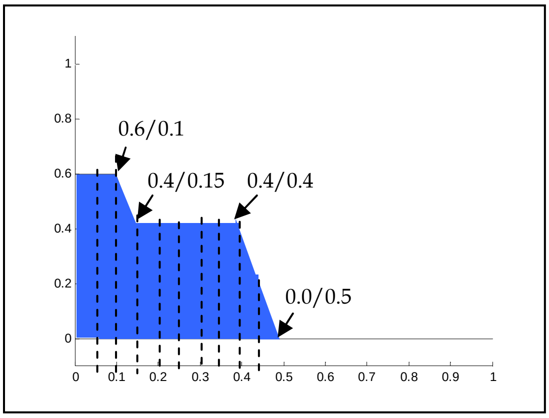


Figure 3.8
An illustration of defuzzification process

The output of the aggregation process yield to a fuzzy set:

C = 0.6/0.0 + 0.6/0.05 + 0.6/0.1 + 0.4/0.15 + … + 0.4/0.4 + 0.45/0.2 + 0.0/0.5

Then, using (3.5) at sampling points z_j = 0.0, 0.05, 0.1,…, 0.5, the final crisp value could be obtained as follows:

$$y_C \cong \frac{\begin{bmatrix} 0\text{x}0.6 + 0.05\text{x}0.6 + 0.10\text{x}0.6 + 0.15\text{x}0.4 + 0.20\text{x}0.4 \\ + 0.25\text{x}0.4 + 0.3\text{x}0.4 + 0.35\text{x}0.4 + 0.4\text{x}0.4 + 0.45\text{x}0.2 + 0.5\text{x}0.0 \end{bmatrix}}{[0.6+0.6+0.6+0.4+0.4+0.4+0.4+0.4+0.4+0.2+0.5]} = \frac{0.84}{4.40} = 0.19$$

In this study, the FRB-1 and FRB-2 models were built using Matlab's Fuzzy Logic Toolbox so that all fuzzy computations were done automatically with the reliable results.

3.2.4. Testing the fuzzy rule-based models

To demonstrate the capability of the fuzzy rule-based (FRB) models as a tool for decision making in assessing ecological sustainability of SFM, the data set from certification process in the Labanan concession were used to test the FRB-1 model. The data set consisted of linguistic values (i.e. *excellent*, *good*, *fair*, *poor*, or *bad*) representing the actual and the passing performances of each indicator, whereas the numeric values corresponding to the linguistic values (as presented in ***Table 3.2***) were derived from the pairwise comparisons matrices using the AHP procedure. In this study, the AHP calculations were done using *ExpertChoice* software (as also practiced in the LEI system) to obtain reliable results.

Since the real data for verifiers were not available, then the FRB-2 model was tested using a hypothetical data set. This data set have been created in such a way that a combination of linguistic values (i.e. *excellent*, *fair*, or *bad*) of the verifiers for a particular indicator would represent the actual linguistic value of such indicator as used in the FRB-1 model. In this case, the numeric values of each linguistic value of the verifiers were assigned purposively.

3.2.5. Analyzing effect of different membership functions

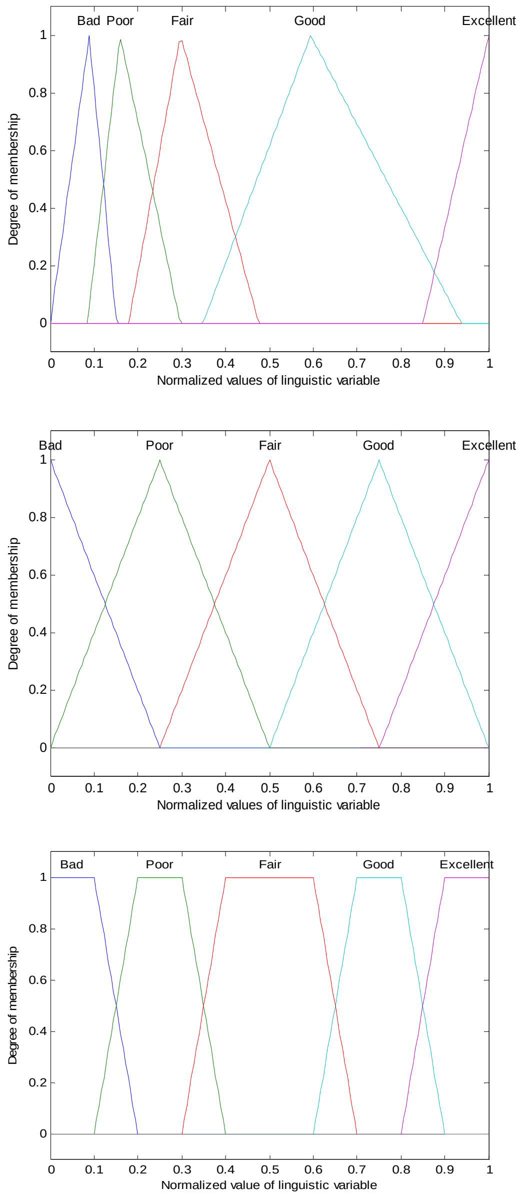
In a FRB model, membership functions play important role in handling uncertainty inherent in linguistic values. In this study, effect of the membership functions (MFs) was analyzed by developing three derivatives of the basic FRB-1 model (called ***FRB-1a***) using different membership functions as follows:

1) FRB***-1b***, which is the FRB-1 model that used the triangular membership functions with the same base-widths (range *a* and *d*) as those used in the FRB-1a model. Hence, parameters of the triangular membership functions were the lower value (a_l): $a_l = a$, the modal value (a_m): $a_m = \overline{x}$, and the upper value (a_u): $a_u = d$, where *a* and *d* are the lower and upper values in trapezoidal membership functions and $\overline{x}$ is average of the crisp values in a particular linguistic value. ***Figure 3.9a*** shows the triangular membership functions used in the FRB-1b model. This model was used to simulate *a pessimistic view* (high uncertainty) about membership degree of the crisp values in a particular linguistic value.
2) ***FRB-1c***, which is the FRB-1 model that used the triangular membership functions with equal widths partitions as depicted in ***Figure 3.9b***. This model was used to simulate a pessimistic view about degree of membership in absence of the pertinent information to construct membership functions for the linguistic values.
3) ***FRB-1d***, which is the FRB-1 model that used the trapezoidal membership functions as depicted in ***Figure 3.9c*** (based on: Phillis and Andriantiatsaholiniaina, 2001). Similar to the FRB-1c, this model was also used to simulate a condition where absence of the pertinent information to derive appropriate membership functions, but decision maker may have an *optimistic view* (low uncertainty) about membership degree of the linguistic values.

Those models were compared to the FRB-1a model and then differences of the model outputs (Δy) were calculated as follows:

$$\Delta y = \frac{y_{FRBi} - y_{FRB1a}}{y_{FRB1a}} \qquad (3.6)$$

where: y_{FRBi} is the overall value of ecological sustainability (ECO) from the *FRB-1b*, *FRB-1c*, or *FRB-1d* model, and y_{FRB1a} is the overall value of ECO from the *FRB-1a* model. Furthermore, the comparison was also performed in terms of differences between the overall actual and overall passing value of ECO as well as associated their linguistic values obtained from those models.



a) The triangular MFs representing *a pessimistic view*

where:
Bad = [0 0.089 0.151]
Poor = [0.085 0.159 0.297]
Fair = [0.179 0.297 0.476]
Good = [0.348 0.594 0.938]
Excellent = [0.85 1 1]

b) The triangular MFs representing *a pessimistic view* when absence of pertinent information

where:
Bad = [0 0.089 0.151]
Poor = [0.085 0.159 0.297]
Fair = [0.179 0.297 0.476]
Good = [0.348 0.594 0.938]
Excellent = [0.85 1 1]

c) The trapezoidal MFs representing *an optimistic view* when absence of pertinent information

where:
Bad = [0 0 0.1 0.2]
Poor = [0.1 0.2 0.3 0.4]
Fair = [0.3 0.4 0.6 0.7]
Good = [0.6 0.7 0.8 0.9]
Excellent = [0.8 0.9 1 1]

Figure 3.9. The triangular and trapezoidal membership functions used in analyzing effect of membership functions in the FRB-1 model

3.2.6. Comparison of the assessment methods and simulation

It is important to see how the outputs from the fuzzy rule-based models (especially FRB-1) would approximate the outputs from the existing method (AHP) of the LEI system. Therefore, the comparisons between two methods were made in terms of the overall values (of both actual and passing performances) and final grade of certification.

To facilitate the comparison, the AHP method was also used to analyze the same data set as the one used in the FRB-1 models. In this case, the AHP model (including all the required pairwise comparison matrices), which was developed by LEI using the *ExpertChoice* software, was adopted to derive the overall values as well as the final grade of certification.

To determine the final grade of certification (whether *gold*, *silver*, *bronze*, *copper*, or *zinc*), the grading procedure as presented in ***Table* 2.2** were applied to the outputs of the FRB-1 models and the AHP method.

Furthermore, it was also considered necessary to simulate some possible assessments in order to demonstrate capabilities of the FRB-1 models, particularly to address the compensation issue as may appear in the AHP method. Therefore, two simulations using two hypothetical data sets were carried out as follows:

- **Simulation 1**, which simulated an assessment with condition that the actual performances of the indicators are higher or equal to their passing performances. This condition would be an opposite to the assessment data of the Labanan concession. It was hypothesized that in such condition both of the methods would reveal a passing condition (at least *bronze* grade) of certification.
- **Simulation 2**, which simulated an assessment with a condition that the actual performances of some important indicators have lower performances (*bad* or *poor*) than those of the other indicators. It was hypothesized that in such condition the compensation phenomena would happen in the AHP method, but it would not happen in the FRB-1 models.

Then comparisons of the simulations results obtained from the FRB-1 models were made in terms of the overall values of ecological sustainability, the grade of certification and the decision whether pass or fail from the certification process.

Chapter 4

Results and Discussion

This chapter presents the results and discussion about the rule base, description of the data that were used to test the FRB model, assessment of ecological sustainability using the FRB models, sensitivity analysis of the FRB models, comparison of the FRB models with the existing decision making method of the LEI system, and simulations of the FRB models. The last part of this chapter discusses some perspectives on strengths and weaknesses as well as practical application and future development of the FRB model.

4.1. The Rule Base to Assess Ecological Sustainability of SFM

One of the results of this study was the rule base which has been elicited from the expert knowledge. Basically, the rule base is a model of the logical thinking of the experts in assessing various indicators and aggregating their values to come up with an overall value indicating achievement of ecological sustainability of SFM. ***Appendix B*** shows the complete rule base that was used in the fuzzy rule-based model 1 (FRB-1), whereas ***Appendix D*** shows the additional rule base that was used in the FRB-2 model. The main arguments and logical thinking of the experts used to derive the rule base for the FRB-1 model are discussed in the ***Section 4.1.1***, whereas those for the FRB-2 are discussed in ***Appendix D***.

4.1.1. Knowledge building

This section explains the backbone arguments obtained from the experts to derive the rule base for aggregating different parts of the hierarchy starting at the indicator level up to the principle level as shown in ***Figure 4.1*** (which is a simplification of ***Figure 1.1***). For proper meaning and description of the indicators, see ***Appendix A***.

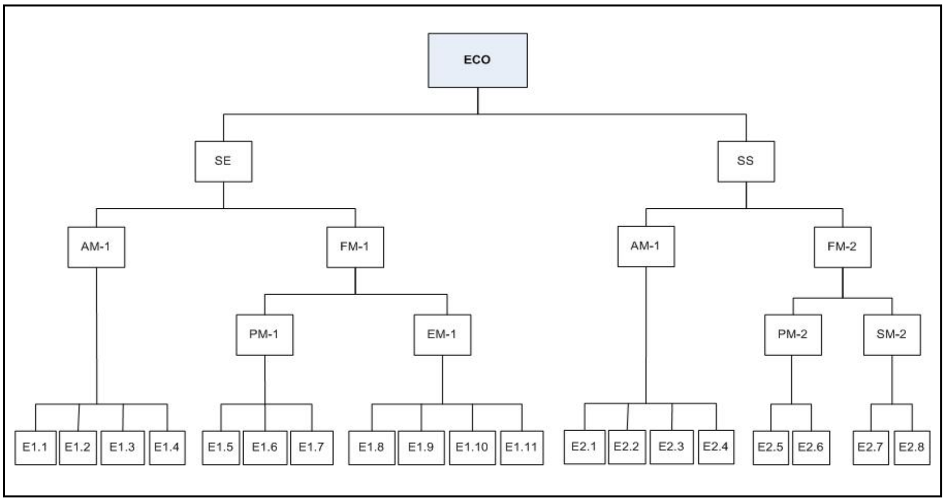


Figure 4.1
A simplified hierarchy of ecological sustainability

1). Area Management under the stability of ecosystem criteria (AM-1)

Performance of area management (AM-1) depends on performances of indicator E1.1, E1.2, E1.3, and E1.4. Indicator E1.1 was considered by the experts as the most important indicator, because the existence of a well-functioning protected area is absolutely required in a forest management unit (FMU). The second important indicator was E1.4 which implies the real condition of flora and fauna in the protected area. The third important indicator was E1.3, which is delineation of the protected area. Indicator E1.2 was considered by the experts as least important because disturbances would only affect the size of the protected area. The indicator E1.1 and E1.4 were key indicators which have dominant effects to the AM-1 performance. In this case, the AM-1 performance should not be better than performance of these indicators. The lower performances (i.e. *poor* or *bad*) of these indicators can not be compensated by the other indicators. If they are bad, then the AM performance will be bad as well. If they have high performances (i.e. *excellent* or *good*) but the other two indicators have low performances (i.e. *poor* or *bad*), then the AM performance will decrease. As an example of a real situation, it is obvious that if the proportion of protected area (as assessed by E1.1) is good and the real condition of flora and fauna (as assessed by E1.4) is also good but there is a high disturbance to the protected area (as assessed by E1.2), then the AM-1 performance will be fair. The complete rule base for assessing performance of the area management (AM-1) is presented in ***Appendix B.1.1***.

2). Production Management under the stability of ecosystem criteria (PM-1)

Performance of production management (PM-1) is assessed by indicator E1.5, E1.6, and E1.7. Indicator E1.5 was considered by the experts as the most important indicator because the ecosystem stability depends highly on condition of forest structure and plant species composition. Indicator E1.6, which assesses impact intensity on soil, and indicator E1.7, which assesses impact on water, were considered by the experts as second and third important indicators, respectively. The extreme performance of the indicator E1.5 dominates the PM performance. If a concession has an excellent forest structure and plant species composition, even if the impact of production activities on soil and water is high, then we can still consider that the performance of PM-1 is good because the impact on soil and water might occur in non-forested areas, such as in forest roads. Indeed, in many cases, a good condition of forest structure has important role to minimize the impact on soil and water due to erosion. However, the performance of PM-1 can be limited by the lower performances (i.e. *poor* or *bad*) of indicator E1.6 and E1.7. It is also important to note here that compensation is not allowed, so that the PM-1 performance can not be better than the E1.5 performance. ***Appendix B.1.2*** presents the complete rule base to assess the PM-1 performance.

3). Environmental Management under the stability of ecosystem criteria (EM-1)

Indicator E1.8, E1.9, E1.10, and E1.11 assess the effectiveness of environmental management related to recovering forest structure, impact controlling on soil, impact controlling on water, and counseling on forest preservation, respectively. Indicator E1.8 was considered by the experts as the most important, E.19 was the second important, E1.10 was the third important, and E1.11 was the less important indicator. Performance of EM-1 depends highly on the performance of either indicator E1.8 or E1.9. If their performances are bad then the EM-1 performance will be bad as well. However, the EM-1 performance can also be affected by the lower performance of indicator E1.10 and E1.11. The complete rule base to assess the EM-1 performance can be seen in ***Appendix B.1.3***.

4). Forest Management under the stability of ecosystem criteria (FM-1)

In relation to the stability of ecosystem criteria, performance of forest management (FM-1) is assessed based on performances of production management (PM-1) and environmental management (EM-1) aspects. The production management was considered by the experts as the first important aspect because it implies performance of the output indicators which deal with the preventive efforts to minimize impacts on the forest ecosystem. The environmental management was considered by the experts as the second important aspect because it implies performance of the process indicators which concern with the impact management. Therefore, performance of production management would dominate the FM performance. However, low performance (*poor* or *bad*) of the environmental management can also limit the FM performance. The detailed rule base for assessing the FM performance can be seen in ***Appendix B.1.4***.

5). Stability of ecosystem criteria (SE)

The stability of ecosystem criteria consists of two main aspects, i.e. area management (AM-1) and forest management (FM-1). Actually, in the LEI system the order of importance of these inputs may vary depending on the typology of forest management unit that is being assessed. However, in the current study AM-1 was considered by the experts as the most important because it implies effort of the forest management unit to allocate some parts of the concession area for the protected area. The forest management (FM-1) was considered by the experts as less important since this aspect concerns more with the application of environmental technologies to minimize impacts of production activities. In the context of ecosystem stability, existence of the protected area is absolutely required to maintain sources of biodiversity in the concession area. Therefore, performance of area management will highly affect the stability of ecosystem. The AM-1 performance will dominate the ecosystem stability performance. The FM-1 performance will also affect the ecosystem stability performance when it has a low performance (i.e. *poor* or *bad*). ***Appendix B.1.5*** provides the detailed rule base for assessing performance of ecosystem stability.

6). Area Management under the survival of endangered species criteria (AM-2)

Performance of area management (AM-2) with respect to survival of endangered species is assessed by indicator E2.1, E.2.2, E2.3, and E2.4. These indicators imply performance of a series of activities that should be accomplished by a FMU in order to support the survival of endangered species in the concession area. In this case, the experts considered that the most important indicator is E2.1 which assesses performance of the protected area that has been allocated by the FMU for protecting endangered species.

The second important was indicator E2.4 which assesses the real condition of endangered species in the protected area. These two indicators play important role in assessing the AM-2 performance. If their performances are bad then performance of the area management is also bad. However, for intermediate performances, these indicators could compensate each other, particularly if the real condition of endangered species is considered as good. Indeed, the main purpose of area management in such case is to have a good condition of the protected area for survival of endangered species. In addition, indicator E2.3 was considered as third important, and indicator E2.2 was the least important indicator. Performance of indicator E2.3 would decrease the AM-2 performance if there is high damage intensity to endangered species. The low performance of indicator E2.2, which implies that the FMU has not delineated properly the protected area, could also decrease the AM-2 performance. It is important to note here that since the essence of the indicators refers to the same activities on area management, then the experts considered that in general the rule base for assessing performance of AM-2 using these indicators would be similar to those for assessing the AM-1 performance of ecosystem stability criteria, as presented in ***Appendix B.2.1***.

7). **Production Management under the survival of endangered species criteria (PM-2)**

Indicator E2.6, which assesses the impact intensity of production management (PM-2) activities towards endangered wildlife animals species and their habitat, was considered by the experts as the most important indicator. Indicator E2.5 which assesses such impact on endangered plants species was considered by the experts as the second important indicator. The experts argued that the impact of production activities towards wildlife animal species is more measurable than towards endangered plant species. Therefore, performance of the PM-2 depends highly on the performance of indicator E2.6, particularly in the extreme cases (i.e. *excellent* or *good*). However, the lower performance of indicator E2.5 can also limit the PM-2 performance. The complete rule base for assessing the PM-2 performance is presented in ***Appendix B.2.2***.

8). **Social Management under the survival of endangered species criteria (SM-2)**

Indicator E2.8 was considered as the most important and indicator E2.7 was less important. It is easier to assess the security of endangered wildlife animal species (as assessed by E2.8) than that of endangered plant species, because the existence of endangered plant species (as assessed by E2.7) is very rare in most concession areas. Therefore, performance of indicator E2.8 dominates the performance of social management (SM) activity, particularly for the extreme performance. For instance, if performance of indicator E2.8 is bad then the SM performance will be bad as well. The complete rule base for assessing the SM performance can be seen in ***Appendix B.2.3***.

9). **Forest Management under the survival of endangered species criteria (FM-2)**

Performance of forest management with respect to the criteria of survival of endangered species depends on the performance of two aspects, i.e. production management (PM-2) and social management (SM-2). The experts considered that the production management is more important than social management. The reason was that the survival of endangered species depends highly on production management activities, whereas interventions of the social management would only affect the communities' awareness on the importance of survival of endangered species. In addition, the impact intensity of production management to the survival of endangered species encompasses large area and affects all species in long terms, whereas social pressures to the endangered species have less impact. In this case, the extreme performance of PM-2 dominates the FM-2 performance and a little compensation may occur when the SM-2 has excellent performance. ***Appendix B.2.4*** presents the complete rule base to assess the FM-2 performance.

10). Survival of endangered species criteria (SS)

Survival of endangered species in a forest management unit is affected highly by the activities of area management (AM-2) and forest management (FM-2). In the current study, forest management was considered by the experts as the most important aspect affecting the survival of endangered species, because the forest management activities (especially production management) will have significant impacts to the survival of endangered species. Therefore, low performances (i.e. *poor* or *bad*) of FM-2 can not be compensated by the high performances of AM-2. However, in the middle grade a little compensation may occur, particularly when the AM-2 performance is superior to FM-2. Based on these arguments, the complete rule base for assessing performance of the survival of endangered species is presented in ***Appendix B.2.5***.

11). Principle of sustainability of ecological function

Sustainability of ecological functions of SFM in the LEI system is assessed based on two criteria, i.e. stability of ecosystem (SE) and survival of endangered species (SS). The experts considered that the stability of ecosystem is the most important criterion. It means that a forest management unit should have a better performance of ecosystem stability in order to achieve sustainability of ecological functions. The survival of endangered species was considered by the experts as the second important criterion. The reason is that the ecosystem stability, which encompasses ecological functions in a broader sense, could indicate the existence of a well-managed forest ecosystem in a landscape scale, while the survival of endangered species focuses only on the species approaches in a narrow scale. Accordingly, if performance of the SE is good and even the SS performance is poor then the overall ecological functions can be considered as good because the endangered species would still be able to survive in a stable forest ecosystem. Therefore, performance of ecosystem stability dominates the output performance. However, the low performance (*poor* or *bad*) of the SS can limit the output performance as well. It is important to note here that for developing fuzzy rule-based models in this study, performance of ecological sustainability was considered directly as the certification grade (i.e. *gold*, *silver*, *bronze*, *copper*, or *zinc*), as shown in ***Appendix B.3***.

4.1.2. Interpretation of the rule base

As shown in ***Appendix B*** and ***Appendix D***, all the rule bases are presented in decision tree forms so that one can easily read or (if necessary) revised. The rules were arranged based on the order of importance of the verifiers, the indicators or the other elements of the hierarchy. Such rule arrangement simulated the way of thinking of the experts, which is the way they usually assess ecological sustainability of SFM by considering the order of importance of the elements (e.g. indicators, criteria) in the hierarchy. As an example, ***Figure 4.2*** shows the rules to assess performance of the production management under survival of endangered species criteria (PM-2) based on performance of the indicator E2.5 and the indicator E2.6. The rules are interpreted as a series of *if-then* statements, such as:

- IF indicator E2.6 is *excellent* AND indicator E2.5 is *excellent*, THEN production management (PM-2) is *excellent*.
- IF indicator E2.6 is *bad* THEN production management (PM-2) is *bad*.

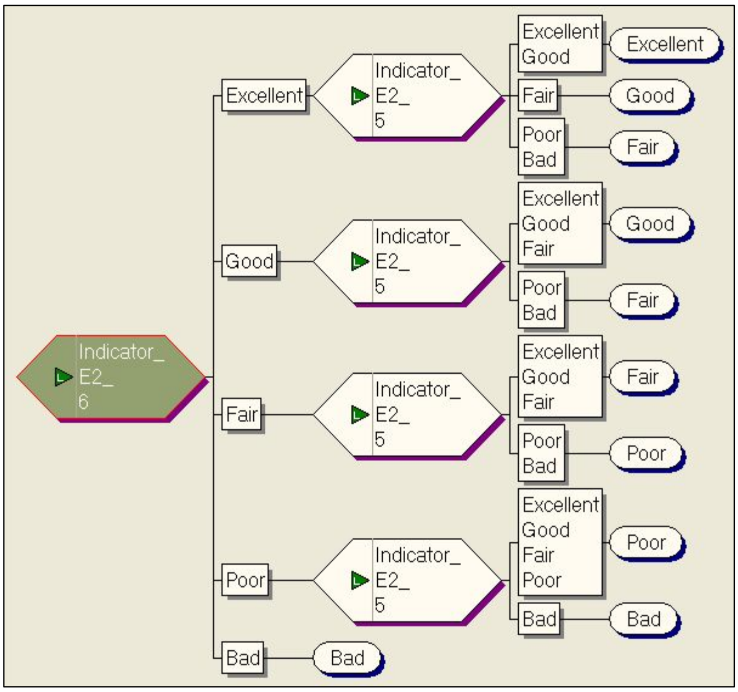


Figure 4.2. The rules used to assess performance of the production management (PM-2)

It is obvious that the number of rules (*if-then* statements) depends highly on the number of the linguistic variables and the linguistic values. For the production management (PM-2) there will be 25 rules if all possible combinations are made. However, based on the expert knowledge the number of rules could be decreased into 21 rules by eliminating unnecessary rules. For instance, experts argued that if the performance of indicator E2.6 is bad then performance of the production management (PM-2) will be bad as well whatever performance of the indicator E2.5 is. The statement "IF indicator E2.6 is *bad* THEN performance of production management (PM-2) is *bad*" is sufficient to represent such expert's arguments. Based on this approach, the total number of rules used in the FRB-1 model was 1103 rules and that in the FRB-2 model was 1380 rules.

4.2. Description of the Data Set

This study used the assessment data on ecological aspects of SFM obtained from the certification process in the Labanan concession. The data consisted of actual and passing performances as presented in ***Table 4.1***.

Table 4.1. The actual and passing performance data of the Labanan concession used as inputs for the FRB-1 models

Indicator	Actual value		Passing value		Indicator	Actual value		Passing value	
	Verbal	Crisp	Verbal	Crisp		Verbal	Crisp	Verbal	Crisp
E1.1	*Poor*	0.129	Fair	0.325	E2.1	Fair	0.325	Fair	0.325
E1.2	Poor	0.160	Poor	0.160	E2.2	Fair	0.303	Fair	0.303
E1.3	*Fair*	0.239	Good	0.436	E2.3	Fair	0.416	Fair	0.416
E1.4	*Fair*	0.405	Poor	0.265	E2.4	Fair	0.405	Fair	0.405
E1.5	*Good*	0.571	Fair	0.310	E2.5	Fair	0.310	Fair	0.310
E1.6	Fair	0.308	Fair	0.308	E2.6	Fair	0.239	Fair	0.239
E1.7	Fair	0.303	Fair	0.303	E2.7	Fair	0.242	Fair	0.242
E1.8	Fair	0.242	Fair	0.242	E2.8	Fair	0.242	Fair	0.242
E1.9	Fair	0.242	Fair	0.242					
E1.10	Fair	0.242	Fair	0.242					
E1.11	Fair	0.242	Fair	0.242					

The actual values show real performances of the forest management unit with respect to the ecological indicators of SFM. These values were judged by the assessors based on their observations in the field. The passing values, which were judged independently by the Expert Panel II team, show the expected minimum performances of each indicator that should be achieved by the concession. Hence, the overall passing value will provide a standard to judge the actual performance of the forest management unit. As shown in ***Table 4.1***, each indicator has the actual and the passing values represented in terms of linguistic values (such as *excellent*, *good*, *fair*, *poor* or *bad*) and crisp values. In the LEI system, the linguistic values are verbal judgments given by the assessors and the experts to represent performance of an indicator, whereas the crisp values are numerical representations of such judgments that are used to aggregate mathematically the indicator values using the AHP method. The crisp values are taken from the normalized crisp value derived from pairwise comparisons as presented in ***Table 3.2***.

From ***Table 4.1***, it can be seen that most of the indicators have the same actual and passing value that is *fair*. There were only two indicators whose actual values were above the passing ones, namely the indicator E1.4 and the indicator E.5. There were also two indicators whose actual values were below the passing ones, namely the indicator E1.1, which is the most important indicator, and the indicator E1.3. Ideally, a forest management unit should have actual performances greater than passing performances to achieve a better level of the ecological sustainability. However, in the case of Labanan concession, the actual performances seemed to be equal to or even worst than the passing performances. Accordingly, by examining these raw data, one might say that Labanan concession was not able to demonstrate a good performance with respect to ecological aspects of SFM.

4.3. Assessment Using the FRB-1 Model

Based on the data set of the Labanan concession, assessment of the ecological sustainability was carried out using the fuzzy rule-based model (called FRB-1) developed in this study. ***Table 4.2*** and ***Table 4.3*** present the results of the FRB-1 model using the actual and the passing performance data, respectively.

Table 4.2. ***Assessment of ecological sustainability using the FRB-1 model and the actual performance data***

Variable	FRB output	Linguistic value of the output
Production management (PM-1)	0.6245	Good(1.0)
Environmental management (EM-1)	0.2237	Poor(0.621), Fair(0.379)
Production management (PM-2)	0.2716	Fair(0.785), Poor(0.215)
Social management (SM-2)	0.2745	Fair(0.809), Poor(0.191)
Area management (AM-1)	0.1441	Poor(0.895), Bad(0.105)
Forest management (FM-1)	0.5124	Good(0.814)
Area management (AM-2)	0.3247	Fair(1.0)
Forest management (FM-2)	0.3023	Fair(1.0)
Stability of ecosystem (SE)	0.1711	Poor(1.0)
Survival of endangered species (SS)	0.3219	Fair(1.0)
Ecological sustainability (ECO)	**0.1813(Copper)**	Copper(0.981), Bronze(0.019)

Table 4.3. ***Assessment of ecological sustainability using the FRB-1 model and the passing performance data***

Variable	FRB output	Linguistic value of the output
Production management (PM-1)	0.3219	Fair(1.0)
Environmental management (EM-1)	0.2237	Poor(0.621), Fair(0.379)
Production management (PM-2)	0.2716	Fair(0.785), Poor(0.215)
Social management (SM-2)	0.2745	Fair(0.809), Poor(0.191)
Area management (AM-1)	0.1488	Poor(0.967), Bad(0.033)
Forest management (FM-1)	0.2560	Fair(0.653), Poor(0.347)
Area management (AM-2)	0.3247	Fair(1.0)
Forest management (FM-2)	0.3023	Fair(1.0)
Stability of ecosystem (SE)	0.1795	Poor(0.996), Fair(0.004)
Survival of endangered species (SS)	0.3219	Fair(1.0)
Ecological sustainability (ECO)	**0.1825(Copper)**	Copper(0.970), Bronze(0.029)

The FRB-1 model generated the outputs for each linguistic variable based on the crisp inputs of the indicator level through a series of fuzzy calculations: fuzzification, fuzzy inference, and defuzzification. To give a better understanding on how the FRB-1 model has worked, the following paragraphs discuss briefly the fuzzy calculations involved in generating the output of production management (PM-2) based on the actual values of the indicator E2.5 and the indicator E2.6 (see also ***Section 3.2.3***):

- At the first step, the FRB-1 fuzzified the crisp value of the indicator E2.5 (0.310 as *fair*) using the trapezoidal membership functions (***Figure 4.3***) into 1.0 (*fair*), whereas the crisp value of the indicator E2.6 (0.239 as *fair*) was fuzzified into 0.51 (*fair*) and 0.49 (*poor*).

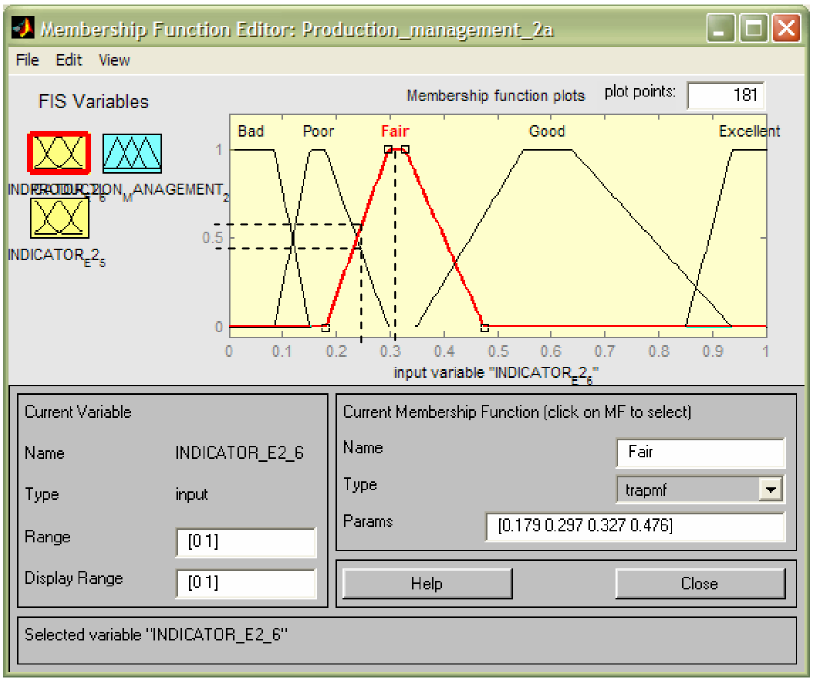


Figure 4.3. ***The fuzzification of the crisp values of the indicator E2.5 and E2.6 in the FRB-1 model***

- Then, the fuzzified values were used as inputs for the fuzzy inference system to activate the appropriate rules in the model. ***Figure 4.4*** shows the fuzzy inference process using the rules as presented in ***Figure 4.2***. Since the indicator E26 had two linguistic values: *fair* and *poor*, and the indicator E2.5 had one linguistic value: *fair*, then the model activated only the following rules:
    - Rule 13: IF indicator E2.6 is *fair* AND indicator E2.5 is *fair* THEN production management is *fair*.
    - Rule 18: IF indicator E2.6 is *poor* AND indicator E2.5 is *fair* THEN production management is *poor*.

  For each rule, the individual fuzzy conclusion was derived by taking a minimum value (i.e. using MIN-operator) of the membership degrees of each rule. The individual conclusions were aggregated using maximum (MAX) operator to generate the overall fuzzy conclusion.

- In the next step, the FRB-1 model performed defuzzification of the overall fuzzy conclusion to generate the crisp value 0.249 and its corresponding linguistic value as the output of the production management variable.

The similar processes were carried out simultaneously by the FRB-1 model by taking the crisp values produced from defuzzification as inputs for fuzzy calculations starting at the indicator level to the principle level of the hierarchy.

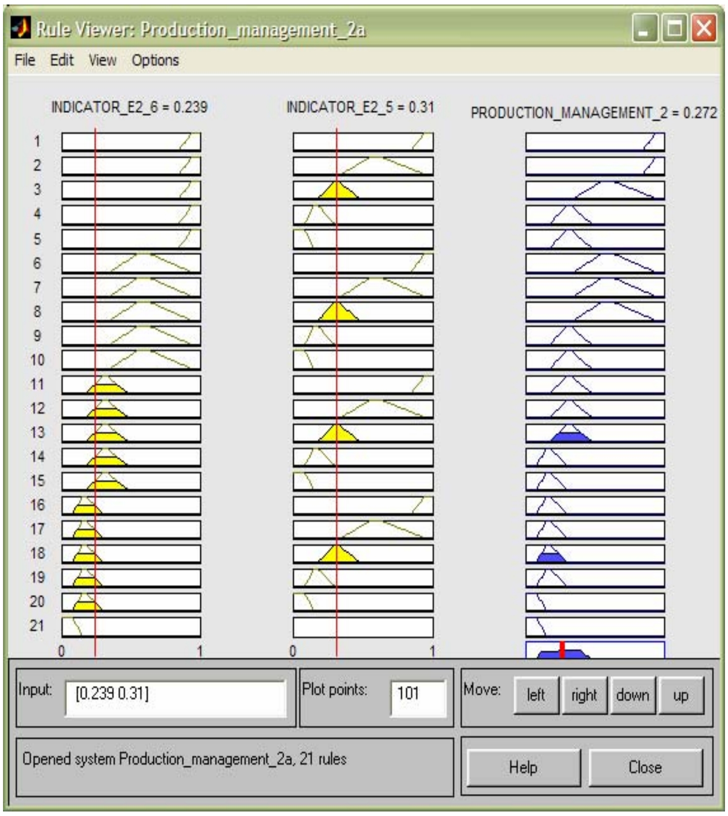


Figure 4.4. ***The fuzzy inference process of generating the PM-2 output***

From ***Table 4.2*** and ***Table 4.3***, it can be seen that the FRB-1 model produced the outputs in terms of the numerical values as well as their corresponding linguistic values. A numerical value represents performance index of a particular linguistic variable which can be interpreted using verbal language as indicated by its linguistic value. For instance, the performance index of production management (PM-2) is 0.2716 which can be considered as *fair* (with membership degree 0.785) rather than as *poor* (with membership degree 0.215). The similar interpretation of the outputs is applicable for the other linguistic variables. However, the most important outputs of the FRB-1 model are the overall actual value and the overall passing value of ecological sustainability (ECO), because they indicate the overall performances of the forest management unit with respect to ecological aspects of SFM. Therefore, the other outputs should be considered as intermediate outputs to eventually come up with the overall performance values.

Based on the FRB-1 model, the overall actual value of ecological sustainability of the Labanan concession was 0.1813 which referred to the *copper* grade (with 0.981 membership degree) and the *bronze* grade (with 0.019 membership degree), and the overall passing value was 0.1825 which referred to the *copper* grade (with 0.970 membership degree). There are two approaches on how to use these outputs to determine the certification grade, either using the crisp values or the linguistic values.

The first approach is that the final grade of certification is calculated based on the overall (crisp) values of actual and passing performances. This approach uses the grading procedure as practiced in the LEI system (intervals are calculated as shown in ***Table 2.2***). ***Table 4.4*** shows the grading for each certification grade that was calculated based on the overall values from the FRB-1 model.

Table 4.4. The grading of the certification grades based on the FRB-1 outputs

Certification grade	Interval of the grade	
	Lower	**Upper**
Gold	0.7275	1.0000
Silver	0.4550	0.7274
Bronze	0.1825	0.4549
Cooper	**0.0913**	**0.1824**
Zinc	0.0000	0.0912

By comparing the overall actual value from the FRB-1 model (i.e. 0.1813) to the appropriate interval above, the final grade of certification for the Labanan concession was *copper*, which means that the concession has failed to achieve ecological sustainability of SFM. In this approach, the difference between the overall actual and the overall passing values is a key to determine the certification grade, although the difference may not be so significant. Interestingly, the results of the FRB-1 model (***Table 4.2*** and ***Table 4.3***) has also showed that the difference between the two overall values was only 0.0012. The possible reason of this small difference was that both the actual and the passing performance data (see ***Table 4.1***) were not so different from each other, where most of them referred to the *fair* performances.

The second approach to determine the final grade of certification is merely using the linguistic values of ECO. As mentioned above, there are two linguistic values for both the overall actual and the overall passing performances: *copper* and *bronze*. However, since *bronze* has a very low degree of membership, then we can consider that the almost certain value for the overall actual and the overall passing performance is *copper*. It means that based on the actual condition of Labanan concession, the assessor team has considered that the appropriate certification grade was *copper*. Similarly, the Expert Panel II team, who judged independently the passing values of each indicator, has also considered that the certification grade for Labanan concession was *copper* as well. Since both of the teams had the same decision, then we can conclude that the final grade of certification for the Labanan concession was *copper*.

Since application of the FRB model for forest certification in the LEI system is still a research issue, see also other studies were carried by Jeganathan (2003) Kuswandari (2004), it is still difficult to determine which approach is more appropriate to be used for determining the certification grade based on the FRB model. As a tool for decision making, the model can only provide some choices to make a decision, whereas the final decision should be made by the decision makers. However, the following considerations are useful to decide which approach would be appropriate for determining the certification grade:

- The first approach is more appropriate to be used when decision makers want to determine the final grade of certification based on both performances of actual and passing. This approach seems to be acceptable since it is already implemented in the existing method of the LEI system. This approach was used in this study to compare the results obtained from the FRB-1 models with those from the existing method.
- The second approach is useful when an assessment is only made based on the actual performance data and decision makers want to get directly the certification grade from the model. This approach has been used by Phillis and Andriantiatsaholiniaina (2001) who developed FRB model to assess sustainable development of some countries. However, this approach requires a well-designed membership function of each grade to obtain a reliable certification grade.

Further analysis of the FRB-1 model can be made by comparing the results to those obtained from the existing method (AHP) as will be discussed in ***Section 4.6***.

4.4. The effect of membership functions

The previous results were produced by the FRB-1 model (called ***FRB-1a***) that used the trapezoidal membership functions derived from the available data, which was the pairwise comparisons of the linguistic values at indicator level, and by considering that a particular linguistic (e.g. *excellent*, *fair*, or *bad*) had a certain range of membership. In other words, the FRB-1a model represents an optimistic view (low uncertainty) about membership degree of the crisp values in a particular linguistic value. The interesting issues related to the effect of membership functions in the FRB model are:

- What would be the outputs if uncertainty associated with the linguistic values is high?
- What would be the outputs if the membership functions derived arbitrary without considering the pertinent information?

In this study, these issues were analyzed by using different membership functions applied in the FRB-1b, FRB-1c, and FRB-1d models. The results are presented in ***Table 4.5***.

The results from the FRB-1b model (***Table 4.5***) revealed that by changing the membership of all the linguistic variables from trapezoidal to triangular membership functions, while preserving the base-widths (ranges of a linguistic value), the overall actual value seemed to be decreased by 0.44% and the overall passing value seemed to be increased by 2.25%. Since the membership functions represent uncertainty (Berkan and Trubatch, 1997), we could say that if the uncertainty became high or decision maker becomes more pessimist about membership degree of the indicator values, then the overall actual value of ECO would become lower and the overall passing value would become higher. However, in this case we could consider that the effect of changing the membership functions was not so significant, where the maximum difference was only 2.25%. As pointed out by Berkan and Trubatch

(1997), the insignificant difference was possibly due to the fact that all the linguistic values used in the models had the same membership functions either trapezoidal (in FRB-1a) or triangular ones (in FRB-1b).

Table 4.5. The outputs obtained from different FRB-1 models

Variable	Actual performance				Passing performance			
	FRB-1a	**FRB-1b**	**FRB-1c**	**FRB-1d**	**FRB-1a**	**FRB-1b**	**FRB-1c**	**FRB-1d**
PM-1	0.6245	0.6269	0.4019	0.2633	0.3219	0.3175	0.3140	0.2951
EM-1	0.2237	0.2391	0.2497	0.2500	0.2237	0.2391	0.2497	0.2500
PM-2	0.2716	0.2739	0.2495	0.2500	0.2716	0.2739	0.2495	0.2500
SM-2	0.2745	0.2764	0.2497	0.2500	0.2745	0.2764	0.2497	0.2500
AM-1	0.1441	0.1465	0.2197	0.1474	0.1488	0.1549	0.2378	0.2413
FM-1	0.5124	0.5450	0.2500	0.2500	0.2560	0.2740	0.2500	0.2500
AM-2	0.3247	0.3228	0.3056	0.2650	0.3247	0.3228	0.3056	0.2894
FM-2	0.3023	0.3015	0.2500	0.2500	0.3023	0.3015	0.2500	0.2500
SE	0.1711	0.1737	0.2476	0.1810	0.1795	0.1810	0.2494	0.2497
SS	0.3219	0.3177	0.2500	0.2500	0.3219	0.3177	0.2500	0.2500
ECO	0.1813	0.1805	0.2499	0.2284	0.1825	0.1866	0.2500	0.2500
ΔECO	**-**	**-0.44%**	**37.84%**	**25.98%**	**-**	**2.25%**	**36.99%**	**36.99%**

Note: *FRB-1a used trapezoidal membership functions (MFs) representing an optimistic view when the data is available, FRB-1b used triangular MFs representing a pessimistic view when the data is available, FRB-1c used triangular MFs representing a pessimistic view when there are no available data, and FRB-1d used trapezoidal MFs representing an optimistic view when there are no available data.*

Surprisingly, as shown in ***Table 4.5***, the FRB-1c and the FRB-1d have produced the overall values much higher than those from the FRB-1a model. The overall actual value increased by 37.84% in the FRB-1c and 25.98% in the FRB-1d. Similarly, the overall passing value increased by 36.99% in both models. By assuming that the FRB-1a is the most appropriate model for the current data, we could consider that such differences were very significant. It was possibly due to both the FRB-1c and the FRB-1d had wider base-widths (range of linguistic value) than those in the FRB-1a model (see ***Figure 3.5*** and ***Figure 3.9***). These results revealed that the membership functions designed arbitrary (not considering pertinent information) would not provide reasonable results.

In the FRB model, the membership functions have a vital role to determine the degree of membership of a given crisp input in an appropriate linguistic value. As discussed in ***Section 4.3***, indeed the FRB model calculated the outputs based on the degree of memberships (fuzzified values) of a particular linguistic value instead of the crisp values. Since a given crisp value could be fuzzified into two linguistic values (e.g. *fair* and *poor*) with different membership degree, then the most reliable membership functions are those that can fuzzify the crisp values into an expected linguistic value with highest membership degree. For instance, if the indicator E1.1 is considered as *poor* with 0.129, then this crisp value should have a higher (or full) membership degree in *poor* rather than *fair*. To verify which of the membership functions used in the FRB-1 model would provide reasonable results, an analysis was made by counting the shifted linguistic values when their associated crisp values (see ***Table 4.1***) were fuzzified using the four FRB-1 models. The results are presented in ***Table 4.6***.

Table 4.6. Percentage of the shifted linguistic values in the FRB-1 models

Data *)	FRB-1a	FRB-1b	FRB-1c	FRB-1d
Actual performance	0%	0%	76.7%	78.9%
Passing performance	0%	0%	68.4%	78.9%

) See* ***Table 4.1*

Table 4.6 provides a proof that the FRB-1a and FRB-1b models could fuzzify all the crisp values into the expected linguistic values. It means that those models performed the fuzzy calculations based on the appropriate inputs values. Meanwhile, the FRB-1c and the FRB-1d could not fuzzify the crisp values as expected in which most of the linguistic values have shifted into other linguistic values. For instance, the value of indicator E1.3 (0.239) shifted from *fair* to *poor*. Consequently, the fuzzy calculations in the FRB-1c and the FRB-1d models were mostly based on inappropriate membership degree of the linguistic values which could lead to the unreliable results. Therefore, it can be concluded that the FRB-1a and the FRB-1b models would provide more reasonable results than the FRB-1c and FRB-1d models. These findings confirmed that the membership functions which were not designed well would give unreliable results. To verify whether or not the difference of membership functions would lead to the different grade of certification, ***Section 4.5*** discusses this issue in detail with a comparison to the results obtained from the existing method (AHP).

4.5. Comparison of the Assessment Methods and Simulations

4.5.1. Comparison of the methods

The results of the FRB-1 model showed that the final grade of certification for the Labanan concession was *copper* with the overall actual value 0.1813 and the overall passing value 0.1825. To confirm whether the existing decision making method of the LEI system would give the same certification grade, the data were also analyzed using the AHP method. The AHP calculations used to derive the overall actual value and the overall passing value of ecological sustainability (ECO) were done using *ExpertChoice* software. ***Table 4.7*** presents a comparison of the results obtained from the AHP method and the FRB-1 models.

Table 4.7. Comparison of the results obtained from the AHP method and the FRB-1 models

Result	AHP method	Fuzzy rule-based (FRB) model			
		FRB-1a	FRB-1b	FRB-1c	FRB-1d
Overall actual value (A)	0.2850	0.1813	0.1805	0.2499	0.2284
Overall passing value (P)	0.2907	0.1825	0.1866	0.2500	0.2500
Interval for upper grades (U)	0.2367	0.2725	0.2711	0.2500	0.2500
Interval for lower grades (L)	0.1450	0.0913	0.0933	0.1250	0.1250
Grade of certification	Copper	Copper	Copper	Copper	Copper
Decision of certification	Fail	Fail	Fail	Fail	Fail

Note: *FRB-1a used trapezoidal membership functions (MFs) representing an optimistic view when the data is available, FRB-1b used triangular MFs representing a pessimistic view when the data is available, FRB-1c used triangular MFs representing a pessimistic view when there are no available data, and FRB-1d used trapezoidal MFs representing an optimistic view when there are no available data.*

As shown in ***Table 4.7***, the AHP method revealed that the certification grade for the Labanan concession was *copper*, which means that the concession has failed in the certification process. Similarly, all the FRB-1 models suggested the *copper* grade as well. Interestingly, the absolute difference between the overall actual value and the overall passing value obtained from the AHP method was only 0.0057, which was also small as those obtained from the FRB-1 models (see also discussion in ***Section 4.3***). In addition, the changes of the membership functions were not so significant to the final grade of certification; hence the models seemed robust. These facts confirmed that assessment of ecological sustainability using the FRB-1 model could provide the approximate results to the existing decision making method.

4.5.2. Simulation

Based on the assessment data of the Labanan concession, the FRB-1 model revealed that the grade of certification was *copper* which means that the concession has failed to achieve the ecological sustainability. To demonstrate capabilities of the FRB-1 model when dealing with different assessment data which could reveal some other possibilities of the model outputs, two simulations were carried out using hypothetical data sets as follows:

a) Simulation 1

This simulation was designed to simulate an assessment when most of the indicators have actual performances higher than their passing performances so that the expected results would reflect a passing condition of certification (minimum a *bronze* grade), as opposite to the previous results. To do so, the hypothetical data as shown in ***Table 4.8*** were used for the simulation.

Table 4.8. The hypothetical data used for the Simulation 1

Indicator	Actual value		Passing value		Indicator	Actual value		Passing value	
	Verbal	Crisp	Verbal	Crisp		Verbal	Crisp	Verbal	Crisp
E1.1	Excellent	1.000	Fair	0.325	E2.1	Good	0.577	Fair	0.325
E1.2	Good	0.568	Fair	0.303	E2.2	Fair	0.303	Fair	0.303
E1.3	Good	0.436	Fair	0.239	E2.3	Good	0.850	Fair	0.416
E1.4	Fair	0.405	Fair	0.405	E2.4	Fair	0.405	Fair	0.405
E1.5	Good	0.571	Fair	0.310	E2.5	Fair	0.310	Fair	0.310
E1.6	Fair	0.308	Fair	0.308	E2.6	Good	0.436	Fair	0.239
E1.7	Good	0.568	Fair	0.303	E2.7	Fair	0.242	Fair	0.242
E1.8	Excellent	1.000	Fair	0.242	E2.8	Good	0.603	Fair	0.242
E1.9	Fair	0.242	Fair	0.242					
E1.10	Good	0.603	Fair	0.242					
E1.11	Good	0.603	Fair	0.242					

It is obvious that all the indicators have performances at least *fair* in which twelve of them have higher actual performances than the passing ones (see ***Figure 4.5***). Considering these data, our intuition would say that the simulated concession should pass from the certification because of its good performances. To prove such hypothesis, the data were analyzed using the AHP method as well as the FRB-1 models with the results as presented in ***Table 4.9***.

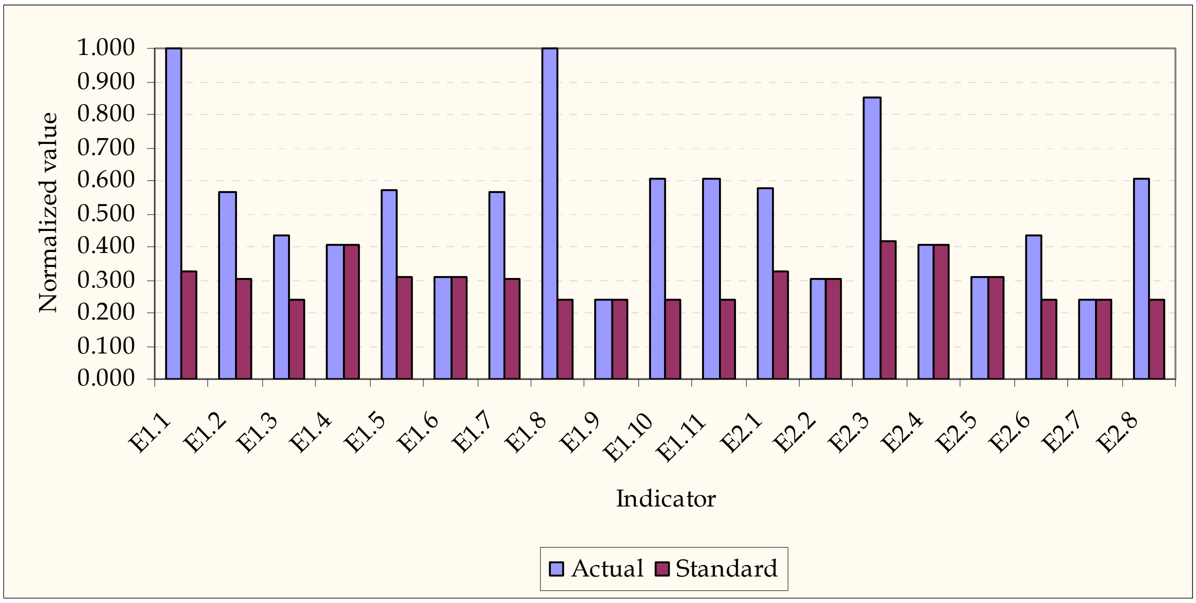


Figure 4.5. Comparison between the actual and the passing performance data used in the Simulation 1

Table 4.9. The results of Simulation 1

Result	AHP method	Fuzzy rule-based (FRB) model			
		FRB-1a	**FRB-1b**	**FRB-1c**	**FRB-1d**
Overall actual value (A)	0.5804	0.6245	0.6270	0.3428	0.2500
Overall passing value (P)	0.3121	0.3128	0.3176	0.2500	0.2500
Interval for upper grades (U)	0.2293	0.2291	0.2275	0.2500	0.2500
Interval for lower grades (L)	0.1561	0.1564	0.1588	0.1250	0.1250
Grade of certification	Silver	Silver	Silver	Bronze	Bronze
Decision of certification	Pass	Pass	Pass	Pass	Pass

Note: *FRB-1a used trapezoidal membership functions (MFs) representing an optimistic view when the data is available, FRB-1b used triangular MFs representing a pessimistic view when the data is available, FRB-1c used triangular MFs representing a pessimistic view when there are no available data, and FRB-1d used trapezoidal MFs representing an optimistic view when there are no available data.*

It can be observed from ***Table 4.9*** that the AHP method produced the overall actual value (0.5804) higher than the passing one (0.3121) which led to the *silver* grade. The same cases were also happen in the outputs of the FRB-1a and the FRB-1b models which also led to the *silver* grade. However, the FRB-1c and the FRB-1d produced the *bronze* grade. This simulation revealed that the FRB-1a and the FRB-1b models could give approximate results to the existing method in which the results (grade and decision of certification) were reasonable as hypothesized before. In this case, the FRB-1c and the FRB-1d model could not give approximate results to the existing method; hence these models would not appropriate to be used to assess ecological sustainability of SFM.

b) Simulation 2

The second simulation was performed to simulate an assessment in which some important indicators have actual performances lower (*bad*) than the other indicators. There were four important indicators (see discussion in ***Section 4.1.1***) used in this simulation, namely:

- Indicator E1.1 (the proportion of a well-functioning protected area) as the most important indicator with respect to the area management activity (AM-1).
- Indicator E1.5 (the damage intensity of forest structure and plant species composition) as the most important indicator with respect to the production management process (PM-1).
- Indicator E1.8 (the effectiveness of damage management of forest structure and composition) as the most important indicator with respect to the environmental management process (EM-1).
- Indicator E2.1 (the proportion of protected area to support existence of endangered species) as the most important indicator with respect to the area management activity (AM-2).

This simulation used the hypothetical data which are presented in ***Table 4.10***.

***Table 4.10. The hypothetical data used for the Simulation** 2*

Indicator	Actual value		Passing value		Indicator	Actual value		Passing value	
	Verbal	Crisp	Verbal	Crisp		Verbal	Crisp	Verbal	Crisp
E1.1	**Bad**	0.079	Fair	0.325	**E2.1**	**Bad**	0.079	Fair	0.325
E1.2	Good	0.568	Fair	0.303	E2.2	Fair	0.303	Fair	0.303
E1.3	Good	0.436	Fair	0.239	E2.3	Good	0.850	Fair	0.416
E1.4	Fair	0.405	Fair	0.405	E2.4	Fair	0.405	Fair	0.405
E1.5	**Bad**	0.082	Fair	0.310	E2.5	Good	0.571	Fair	0.310
E1.6	Fair	0.308	Fair	0.308	E2.6	Fair	0.239	Fair	0.239
E1.7	Excellent	1.000	Fair	0.303	E2.7	Good	0.603	Fair	0.242
E1.8	**Bad**	0.080	Fair	0.242	E2.8	Fair	0.242	Fair	0.242
E1.9	Fair	0.242	Fair	0.242					
E1.10	Good	0.603	Fair	0.242					
E1.11	Good	0.603	Fair	0.242					

As shown in ***Table 4.10***, those four important indicators have *bad* actual performances and the other indicators have high performances, at least *fair* (see ***Figure 4.6***). These four indicators were considered as important ones both in the FRB-1 model (as discussed in ***Section 4.1.1***) and in the AHP method (as showed by their high weights in the AHP model developed by LEI). Accordingly, it is reasonable if in such condition the concession would not pass in the certification process since the performances of most important indicators were *bad*. To prove this hypothesis, the simulation using such data was carried out with the results are presented in ***Table 4.11***.

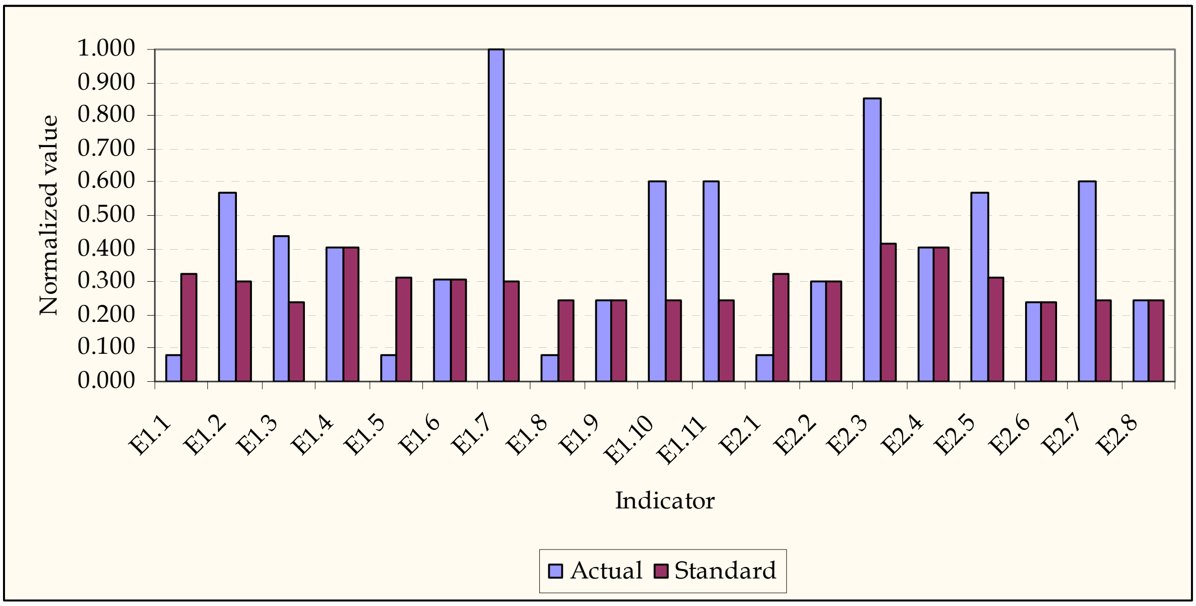


Figure 4.6. Comparison between the actual and the passing performance data used in the Simulation 2

Table 4.11. The results of Simulation 2

Result	AHP method	Fuzzy rule-based (FRB) model			
		FRB-1a	**FRB-1b**	**FRB-1c**	**FRB-1d**
Overall actual value (A)	0.3446	0.0580	0.0799	0.2497	0.0752
Overall passing value (P)	0.3121	0.3128	0.3176	0.2500	0.2500
Interval for upper grades (U)	0.2293	0.2291	0.2275	0.2500	0.2500
Interval for lower grades (L)	0.1561	0.1564	0.1588	0.1250	0.1250
Grade of certification	Bronze	Zinc	Zinc	Copper	Zinc
Decision of certification	Pass	Fail	Fail	Fail	Fail

Note: *FRB-1a used trapezoidal membership functions (MFs) representing an optimistic view when the data is available, FRB-1b used triangular MFs representing a pessimistic view when the data is available, FRB-1c used triangular MFs representing a pessimistic view when there are no available data, and FRB-1d used trapezoidal MFs representing an optimistic view when there are no available data.*

Surprisingly, as shown in ***Table 4.11***, the AHP and the FRB-1 models revealed the different results. The AHP method suggested that the grade of certification was *bronze* which means that the concession would still pass in the certification process. Meanwhile, most of the FRB-1 models suggested that the grade of certification was *zinc* (based on the FRB-1a, FRB-1b, and FRB-1d) and *copper* (based on the FRB-1c) which means that such concession should not pass in the certification process.

To verify which method could give reasonable results, we have to check the hypothetical data carefully. Indeed, as explained before, there were four important indicators had *bad* actual performances. In addition, by considering the expert arguments as used in the rule base related to these indicators (see ***Section 4.1.1***), in which bad performances of these indicators can not be compensated by the good performances of the other indicators, our common sense can accept the hypothesis that in such condition the concession should not pass in the certification process. Therefore, the results of the FRB-1 models were reasonable than those of the AHP method. An anomaly grade (*copper*) has occurred in the FRB-1c model, which suggested that this model was not reliable compare to the other FRB-1 models.

The simulation can prove that compensation has occurred in the AHP method, in which the *bad* performances of the four important indicators have been compensated by the *good* performances of the other less important indicators. Obviously, by examining the actual values (see ***Table 4.10***), the low values of those important indicators had been compensated by the other values. Such compensation has occurred in the AHP method because it uses the weighted summation method to aggregate the indicator values to come up with an overall value of ecological sustainability. Indeed, as warned by Forman and Selly (2002), the compensation would be inevitable when decision making process is carried out using the AHP method. On the other hand, the FRB-1 models used the rule base, which have been designed to avoid such compensations, to aggregate the indicator values so that the compensation has not occurred. In addition, the MIN operator used in the fuzzy inference of the FRB-1 models have provided conservative attitude (Cornelissen et al., 2001) so that the compensation would not occur. It is obvious that using the fuzzy rule-based model, the decision makers would have a full control on how to aggregate the indicator values according to their way of thinking to come up with a reasonable decision of certification.

4.6. Assessment Using the FRB-2 Model

The previous sections have discussed application of the fuzzy rule-based model (called FRB-1) to assess ecological sustainability of SFM using the inputs at the indicator level. Another model, which was developed in this study, is the FRB-2 model which used the inputs at the verifier level. Since there was not a real data set for this model, the FRB-2 model was tested using the hypothetical data as presented in ***Table 4.12***.

Table 4.12. The hypothetical data set used in the FRB-2 model

Indicator	Verifier	Actual value		Passing value	
		Verbal	Crisp	Verbal	Crisp
E1.1	E1.1.1	Fair	0.285	Excellent	1.000
	E1.1.2	Bad	0.176	Excellent	1.000
	E1.1.3	Fair	0.265	Bad	0.109
E1.2	E1.2.1	Fair	0.245	Fair	0.245
	E1.2.2	Bad	0.218	Bad	0.218
	E1.2.3	Excellent	0.550	Excellent	0.550
E1.3	E1.3.1	Fair	0.308	Excellent	1.000
	E1.3.2	Fair	0.300	Fair	0.350
	E1.3.3	Fair	0.250	Excellent	1.000
E1.4	E1.4.1	Fair	0.363	Bad	0.062
	E1.4.2	Fair	0.286	Fair	0.286
	E1.4.3	Fair	0.283	Excellent	0.673
E1.5	E1.5.1	Fair	0.258	Fair	0.325
	E1.5.2	Excellent	0.585	Fair	0.330
	E1.5.3	Excellent	0.689	Fair	0.350

Table 4.12 (continued)

Indicator	Verifier	Actual value		Passing value	
		Verbal	Crisp	Verbal	Crisp
E1.6	E1.6.1	Fair	0.345	Fair	0.345
	E1.6.2	Fair	0.300	Fair	0.300
E1.7	E1.7.1	Fair	0.341	Fair	0.341
	E1.7.2	Fair	0.358	Fair	0.358
E1.8	E1.8.1	Bad	0.037	Bad	0.037
	E1.8.2	Excellent	0.977	Excellent	1.000
E1.9	E1.9.1	Fair	0.331	Fair	0.331
	E1.9.2	Fair	0.260	Fair	0.260
E1.10	E1.10.1	Excellent	0.542	Excellent	0.542
	E1.10.2	Bad	0.020	Bad	0.020
E1.11	E1.11.1	Fair	0.379	Fair	0.379
	E1.11.2	Bad	0.197	Bad	0.197
	E1.11.3	Excellent	1.000	Excellent	1.000
E2.1	E2.1.1	Fair	0.300	Fair	0.300
	E2.1.2	Fair	0.315	Fair	0.315
	E2.1.3	Fair	0.275	Fair	0.275
E2.2	E2.2.1	Fair	0.292	Fair	0.292
	E2.2.2	Excellent	0.484	Excellent	0.484
	E2.2.3	Fair	0.262	Fair	0.262
E2.3	E2.3.1	Fair	0.313	Fair	0.313
	E2.3.2	Bad	0.211	Bad	0.211
E2.4	E2.4.1	Bad	0.021	Bad	0.021
	E2.4.2	Excellent	0.870	Excellent	0.870
	E2.4.3	Excellent	0.638	Excellent	0.638
E2.5	E2.5.1	Fair	0.274	Fair	0.274
	E2.5.2	Excellent	0.781	Excellent	0.781
	E2.5.3	Bad	0.228	Bad	0.228
E2.6	E2.6.1	Fair	0.345	Fair	0.345
	E2.6.2	Fair	0.264	Fair	0.264
E2.7	E2.7.1	Excellent	0.881	Excellent	0.881
	E2.7.2	Bad	0.127	Bad	0.127
E2.8	E2.8.1	Fair	0.324	Fair	0.324
	E2.8.2	Fair	0.377	Fair	0.377

Note: see ***Appendix C*** *for the meaning and description of each verifier*

From ***Table 4.12***, we can see that the FRB-2 model used the inputs starting at the verifier level. In practice, the verifier values may come either from the expert judgments or measurements. By using the hypothetical data above, the FRB-2 model produced the outputs as presented in ***Table 4.13***.

Table 4.13. Assessment of ecological sustainability using the FRB-2 model

Variable	Actual value		Passing value	
	Crisp	Linguistic	Crisp	Linguistic
Indicator level:				
E1.1	0.1479	Poor(0.95), Bad(0.05)	0.3219	Fair(1.0)
E1.2	0.1975	Poor(0.84) Fair(0.16)	0.1975	Poor(0.84), Fair(0.16)
E1.3	0.2712	Fair(0.78), Poor(0.22)	0.6245	Good(1.0)
E1.4	0.2752	Fair(0.82), Poor(0.18)	0.1626	Poor(1.0)
E1.5	0.5373	Good(0.94)	0.3219	Fair(1.0)
E1.6	0.3122	Fair(1.0)	0.3122	Fair(1.0)
E1.7	0.3267	Fair(1.0)	0.3267	Fair(1.0)
E1.8	0.3219	Fair(1.0)	0.3219	Fair(1.0)
E1.9	0.2833	Fair(0.88), Poor(0.12)	0.2833	Fair(0.88), Poor(0.12)
E1.10	0.3224	Fair(1.0)	0.3224	Fair(1.0)
E1.11	0.3753	Fair(0.68), Good(0.14)	0.3753	Fair(0.68), Good(0.14)
E2.1	0.2826	Fair(0.88), Poor(0.12)	0.2826	Fair(0.88), Poor(0.12)
E2.2	0.3043	Fair(1.0)	0.3043	Fair(1.0)
E2.3	0.3229	Fair(1.0)	0.3229	Fair(1.0)
E2.4	0.3219	Fair(1.0)	0.3219	Fair(1.0)
E2.5	0.2919	Fair(0.96), Poor(0.04)	0.2919	Fair(0.96), Poor(0.04)
E2.6	0.3233	Fair(1.0)	0.3233	Fair(1.0)
E2.7	0.3219	Fair(1.0)	0.3219	Fair(1.0)
E2.8	0.3999	Fair(0.51), Good(0.26)	0.3999	Fair(0.51), Good(0.26)
Sub-process level:				
PM-1	0.6251	Good(1.0)	0.3219	Fair(1.0)
EM-1	0.3231	Fair(1.0)	0.3231	Fair(1.0)
PM-2	0.3172	Fair(1.0)	0.3172	Fair(1.0)
SM-2	0.324	Fair(1.0)	0.324	Fair(1.0)
Process level				
AM-1	0.1773	Poor(1.0)	0.1821	Poor(0.97), Fair(0.03)
FM-1	0.6245	Good(1.0)	0.3219	Fair(1.0)
AM-2	0.3093	Fair(1.0)	0.3093	Fair(1.0)
FM-2	0.3219	Fair(1.0)	0.3219	Fair(1.0)
Criteria level:				
SE	0.1813	Poor(0.98), Fair(0.02)	0.1891	Poor(0.91), Fair(0.09)
SS	0.3219	Fair(1.0)	0.3219	Fair(1.0)
Principle level:				
ECO	**0.1871**	**Copper**(0.93), Bronze(0.07)	**0.2046**	**Copper**(0.78), Bronze(0.22)

Note: the parenthesized numbers are membership degrees of the crisp outputs in associated linguistic values

Basically, the outputs from the FRB-2 model were similar to those from the FRB-1 model in which the model could generate the outputs for each variable in terms of crisp values or linguistic values. Moreover, since the FRB-2 model used the inputs at the verifier level, then this model could generate the outputs for the indicator level as well. Interpretation of the outputs is also similar to that of the FRB-1 model. For instance, aggregation of the three verifiers under the indicator E1.1, which had the actual values: *fair* (0.285), *bad* (0.176), *fair* (0.265) (see ***Table 4.12***), has produced the crisp output 0.1479 which could be considered as *poor* (with membership degree 0.95). Similar interpretation is also applicable for the other outputs. The outputs at the indicator level, the sub-process level, the process level, and the criteria level were intermediate outputs to come up with the overall values. Thus, the most important outputs were the overall actual value and the overall passing value of ecological sustainability (ECO), which can be used to determine the certification grade.

Using the similar approaches as used in the FRB-1 model, the certification grade can be determined either based on the linguistic values or the crisp overall values of ECO. Obviously, based on the linguistic values of ECO, the appropriate certification grade was *copper*. Similarly, based on the crisp overall values of ECO, the certification grade was also *copper* because the overall actual value (i.e. 0.1871) was lower than the overall passing value (i.e. 0.2046). However, since the approach to assess ecological sustainability based on the verifier values is not exist in the LEI system, the results obtained from the FRB-2 model can not be compared.

The FRB-2 model suggested an alternative approach to assess ecological sustainability of SFM. Using this model the decision making process could be carried out directly on basis of verifiers instead of indicators. The advantage of this model is that the decision maker can use directly the values of each verifier to obtain the overall values of ecological sustainability as well as the appropriate certification grade.

4.7. Some Perspectives on the Fuzzy Rule-Based Model

The previous sections have discussed the potential application of the fuzzy rule-based (FRB) model as an alternative decision making tool for assessing ecological sustainability of SFM. This section discusses some perspectives about strength and weakness as well as the practical application and future development of the FRB model.

4.7.1. Strength and weakness of the FRB model

Considering the results of this study as well as other relevant studies, the strengths and weaknesses of the fuzzy rule-based model can be discussed as follow:

a) The strength of the FRB model

The strength of the fuzzy rule-based model can be analyzed in some important aspects related to the ability to integrate expert knowledge and accommodate uncertainty. The following paragraphs discuss these aspects in detail.

The main strength of the fuzzy rule-based (FRB) model as a tool for decision making is the ability to integrate expert knowledge (Adriaenssens et al., 2004). As found in the current study, the FRB model can provide a framework for emulating the expert thinking on how the values of the verifiers or indicators should be aggregated logically to come up with a reasonable result of the assessment. The rule base, which consists of a series *if-then* statement, provides a transparent representation of the expert knowledge (Adriaenssens et al., 2004) which can be easily adjusted if any mistakes happened or can be updated with new knowledge if there are additional information. Moreover, the rule base provides a logical approach which allow the decision process to be described in natural language (Ducey and Larson, 1999). Since the FRB model relies on a logical approach instead of merely numerical approach as used in the AHP method, the model would better represent the real interactions among components (e.g. verifiers, indicators, criteria) of the ecological sustainability. In addition, the logical approach would allow the decision maker to control the aggregation process of those components to come up with the expected results. Accordingly, the FRB model developed in this study gives an expected advantage for the LEI system: the model can address the compensation issue (see discussion in ***Section 4.5.2***).

The FRB model has also the ability to accommodate uncertainty (Cornelissen et al., 2001; Ducey and Larson, 1999; Reynolds et al., 2003). Since the assessment of ecological sustainability of SFM is conducted by several experts and all the indicators are assessed using verbal judgment, hence subjectivity and uncertainty of the expert judgments are inevitable in the decision making process. The FRB model can handle uncertainty by using membership functions which define soft thresholds (Cornelissen et al., 2001) for representing uncertainty of the verbal judgments. As discussed in ***Section 4.4***, the trapezoidal membership functions could be used to represent an optimistic view of the decision maker when he/she is more certain about membership of a particular linguistic value (e.g. *excellent*, *fair*, *bad*). Meanwhile, the triangular membership functions could be used to represent a pessimistic view of the decision maker when he/she is very uncertain about membership of a particular linguistic value (Berkan and Trubatch, 1997).

b) The weakness of the FRB model

Despite the strength, the FRB model has some potential weakness particularly due to the huge number of fuzzy rules and subjectivity in constructing membership functions.

As discussed before, the FRB model uses the rule base to emulate the expert thinking. However, the number of rules would increase with increasing of the number of linguistic variables and linguistic values used in the model. In such case, the FRB model would become non-transparent and difficult to be applied (Cornelissen et al., 2001). It is found in the current study that the huge number of rules was required to develop the FRB models, where the FRB-1 model used 1103 rules and the FRB-2 model used 1380 rules. In fact, the eliciting rule base from the expert knowledge is the most difficult part in developing the FRB models.

Although the membership function provides a novel approach in representing uncertainty of linguistic values, its construction is not easy and often considered as too subjective task (Cornelissen et al., 2001). Such difficulty was also faced in this study particularly due to the absence of pertinent information regarding how to determine membership degrees of any crisp values in a particular linguistic value. However, such difficulty and subjectivity were minimized by constructing the membership functions from the available pairwise comparison matrices (of the AHP method) provided by LEI. It was proved that this approach could give the reasonable results.

In summary, compare to the existing method, the FRB model developed in this study provides a better approach to treat explicitly the subjectivity which is inherent in assessing ecological sustainability of SFM. The decision maker should realize that the results obtained from the FRB model are approximation to those of the human thinking.

4.7.2. Practical application and future development

The results of this study suggested that the fuzzy rule-based (FRB) model can be used as an alternative decision making method to assess ecological sustainability of SFM using the LEI system. However, there are still some issues that should be addressed in practical application and future development of the FRB models, particularly related to the model inputs, possibility to extent the proposed method, and urgency to develop a decision support system.

In this study, all the inputs for the FRB models came from the expert judgments. The values for each indicator in the FRB-1 model were derived from the pairwise comparison matrices as used in the AHP method. This approach is still relevant to elicit values for either the FRB-1 model or the FRB-2 model, particularly if the assessment is mainly based on the expert judgments; hence subjectivity could be minimized. Alternatively, the inputs may come from quantitative measurements. This approach seems to be appropriate for the FRB-2 model since many verifiers can be measured quantitatively (see ***Appendix C***). Moreover, for the FRB-2 model, there are two important issues that should be addressed in the future, namely:

1). A detailed guideline on how to assess the verifiers is needed in order to guide the assessors in determining value of each verifier because such guideline does not exist yet in the LEI system. The guideline should provide detailed description of the linguistic values of the verifiers (e.g. *excellent*, *fair*, *bad*) which are used in the model. For the purpose of this study, ***Appendix C*** provides an example of such description.

2). The verification techniques to assess each verifier should be improved. In this context, the use of GIS (geographical information system) and remote sensing techniques would help the assessors to determine a reliable value for each verifier. For the Labanan context, Aguma (2002) has demonstrated that the GIS and remote sensing techniques can be used to assess damages within the river-protected area (indicator E1.3). Such techniques could give more reliable results than those obtained from the conventional techniques, which is mainly based on visual observations, as used by the assessors in the field.

Another issue related to inputs for the FRB model is about membership functions. As discussed in ***Section 4.4***, different shapes of membership functions could give different results. In the FRB model, the membership functions have to be designed well because they have an important role in handling uncertainty of the linguistic values. This study has come up with a simple approach to build membership functions based on statistics of the linguistic values obtained from the pairwise comparison matrices. It was proved that the membership functions derived using this approach could give more reasonable results than those derived arbitrary (without considering the pertinent information). However, since this study only dealt with data from an assessment, it is still needed to further verify the reliability of this approach by using data from other assessments. Therefore, future study on development of the FRB model has to provide a systematic approach on how to construct membership functions based on the expert knowledge or other relevant data.

The FRB models developed in this study have provided approach to assess sustainability of ecological functions of SFM, which is one of the three aspects of SFM in the LEI system. The previous studies conducted by Jeganathan (2003) and Kuswandari (2004) have dealt with the sustainability of the production functions of SFM. Therefore, development of the FRB model to assess sustainability of social functions of SFM is needed in the future in order to provide a comprehensive FRB model that can be used to assess SFM using the LEI system. The methods developed in this study can easily be extended to develop a complete FRB model for the whole LEI system.

In the current study, the FRB models were built up using the Matlab's Fuzzy Logic Toolbox which needs a basic skill on how to operate the software. Therefore, for practical application of the FRB model, it is necessary to develop a decision support system (DSS) that provides user-friendly interfaces and hide necessary fuzzy computations. The DSS should allow the user to adjust and update the rules, to customize shape and range of membership functions, and to assign the inputs derived from expert judgments or field measurements.

Chapter 5

Conclusion and Recommendation

The urgency of finding an alternative decision making method for the LEI system has motivated this study to develop the fuzzy rule-based (FRB) model. The methods and the results of the FRB model have been discussed in the previous chapters. The assessment results of ecological sustainability of SFM have also been compared to those of the existing method (AHP) to ensure that the proposed model is reasonable. Based on the results and findings from this study, the following sections summarize some conclusions and recommendations.

5.1. Conclusions

The following conclusions provide answers to the research questions:

1). The rule base consists of a series of *if-then* statements representing logical thinking of the experts on how they assess and aggregate various verifiers, indicators and criteria to determine an appropriate grade of ecological sustainability of SFM for a particular forest management unit. The rules are arranged based on the order of importance of the verifiers, the indicators or the other elements of the hierarchy. Such arrangement simulates the way of thinking of the experts. The complete rules for assessing ecological sustainability of SFM using the LEI system are presented in ***Appendix B*** and ***Appendix D***.

2). There are two fuzzy rule-based (FRB) models developed in this study: 1) the FRB-1 model that was used to aggregated values starting at the indicator level, and 2) the FRB-2 model that was used to aggregate values starting at the verifier level. Both of the models have similar architectures; the difference is only in the model inputs. The FRB-1 model is similar to the existing method (AHP) in which the model uses the inputs at the indicator level. Meanwhile, the FRB-2 model provides an alternative approach that allows the decision maker to make an assessment based on the verifier values.

3). This study demonstrated a simple approach to build membership functions for the FRB model. The membership functions for each linguistic value (e.g. *excellent*, *fair*, or *bad*) could be built based on statistics (minimum, mean, maximum, and standard deviation) of the linguistic values derived from the pairwise comparison matrices. It was proved that the trapezoidal and the triangular membership functions derived using this approach could give reasonable results compare to those derived arbitrary (without considering the pertinent information).

4). The FRB model can give reasonable results of the assessment. Based on the assessments using the data set of Labanan concession and the hypothetical data set, it was proved that the FRB model can give the same grade and decision of certification as those of the existing method (AHP). The FRB model can give an expected advantage for the LEI system to address the compensation issue.

5). This study revealed that the FRB model is a promising tool for assessing ecological sustainability of SFM with some strengths and weaknesses. The strength of the FRB model is its ability to integrate expert knowledge, accommodate uncertainty of the expert judgments, and avoid compensation. The weakness of the FRB model is the huge number of rules and subjectivity in constructing membership functions.

5.2. Recommendations

The following issues should be considered in future development of the FRB model:

1). It is necessary to develop FRB model to assess sustainability of social functions of SFM, which is not covered by this study and the previous studies, and eventually to assess the whole aspects (production, ecology, and social) of SFM using the LEI system.

2). Further study is required to find out a systematic approach in constructing membership functions based on expert knowledge and other relevant data.

3). Development of a user-friendly decision support system (DSS) is required to support application of the FRB model in a real decision making process of forest certification.

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Appendix A. Description of the ecological indicators of SFM in the LEI system (adopted from: LEI, 2000)

Indicator	Intensity scale (norm) *)
E1.1 Proportion of a well-functioning protected area to the total area that should be protected and has already been stipulated and/or acknowledged by relevant parties	**Excellent:** The protected area size that is functioning well and is confirmed and/or acknowledged by relevant parties is equal to or bigger than the area size that should be protected **Good:** The protected area size that is functioning well and is confirmed and/or acknowledged by relevant parties is only 75 – 100% of the total area size that should be protected **Fair:** The protected area size that is functioning well and is confirmed and/or acknowledged by relevant parties is only 50 – 75% of the total area size that should be protected **Poor:** The protected area size that is functioning well & is confirmed and/or acknowledged by relevant parties is less than 50% (<50%) of the total area size that should be protected **Bad:** The protected area size that is functioning well is less than 50% (<50%) of the total area size that should be protected, and is not confirmed and/or acknowledged by the relevant parties
E1.2 Proportion of a well-managed protected area to the total size that should be protected and has already been delineated in the field	**Excellent**: The realization of boundary delineation of the protected area that is well designed is equal to the total area that should be protected **Good**: The realization of boundary delineation of the protected area that is well designed is 75 – 100% of the total area that should be protected **Fair**: The realization of boundary delineation of the protected area that is well designed is 50 – 75% of the total area that should be protected **Poor**: The realization of boundary delineation of the protected area that is well designed is 25 – 50% of the total area that should be protected **Bad**: The realization of boundary delineation of the protected area that is well designed is less than 25 % (<25%) of the total area that should be protected
E1.3 Intensity of damage in the protected areas, including fire hazards	**Excellent**: No damage in the protected area **Good**: The area size of the damaged protected area is small (<25 %), there is a low degree of damage, and its control efforts are adequate **Fair**: The damaged protected area is small (<25 %), there is a low degree of damage, and its control efforts are inadequate **Poor**: The damaged protected area is small (<25 %), and there is a high degree of damage **Bad**: The damaged protected area is large (>50 %)
E1.4 Condition of flora and/or fauna species diversity in protected area in various forest formations/types within management units	**Excellent**: The diversity of flora and/or fauna in the protected area is greater than or equal to those in the virgin forest and greater than those in the old logged-over area (>20 yrs.) **Good**: The diversity of flora in the protected area is 90 – 100% of those in the virgin forest and the old logged-over area, and the diversity of fauna in the protected area is 80 – 100% of those in the virgin forest and the old logged-over area **Fair**: The diversity of flora in the protected area is 70 – 90% of those in the virgin forest and the old logged-over area, and the diversity of fauna in the protected area is 60 – 80 % of those in the virgin forest and the old logged-over area

Appendix A (continued)

Indicator	Intensity scale (norm) *)
E1.4	**<u>Poor</u>**: The diversity of flora in the protected area is 60 – 70% of those in the virgin forest and the old logged-over area, and the diversity of fauna in the protected area is 40 – 60% of those in the virgin forest and the old logged-over area **<u>Bad</u>**: The diversity of flora in the protected area is < 60% of those in the virgin forest and the old logged-over area, and the diversity of fauna in the protected area is < 40% of those in the virgin forest and the old logged-over area
E1.5 Damage intensity of forest structure and plant species composition	**<u>Excellent</u>**: The community similarity index between the logged-over area and the virgin forest is greater than 50% (>50%), and the amount of utilized plants species that are found in the logged-over area is greater than or equal to the ones found in the virgin forest **<u>Good</u>**: The community similarity index between the logged-over area and the virgin forest is greater than 50% (>50%), and the amount of utilized plants species that are found in the logged-over area > 80% of those found in the virgin forest **<u>Fair</u>**: The community similarity index between the logged-over area and the virgin forest is greater than 50% (>50%), and the amount of utilized plants species that are found in the logged-over area is < 80% of those found in the virgin forest **<u>Poor</u>**: The community similarity index between the logged-over area and the virgin forest is less than 25% (<25%), and the amount of utilized plants species that are found in the logged-over area is > 80% than those found in the virgin forest **<u>Bad</u>**: The community similarity index between the logged-over area and the virgin forest is less than 25% (< 25%), and the amount of utilized plant species that are found in the logged-over area is < 80% of those found in the virgin forest
E1.6 Impact intensity of production management activities on soil	**<u>Excellent</u>**: Low erosion hazard index (IBE <1) and contribution of the management unit to a total suspended soil content in a body of water is low (<100mg/l) **<u>Good</u>**: Low erosion hazard index (IBE <1) and contribution of the management unit to a total suspended soil content in a body of water is moderate (100 – 250mg/l) **<u>Fair</u>**: Low erosion hazard index (IBE <1) and contribution of the management unit to a total suspended soil content in a body of water is high (>100 mg/l) **<u>Poor</u>**: Moderate erosion hazard index (IBE =1) and contribution of the management unit to a total suspended soil content in a body of water is high (>250 mg/l) **<u>Bad</u>**: High erosion hazard index (IBE >1) and contribution of the management unit to a total suspended soil content in a body of water is high (>250 mg/l)
E1.7 Impact intensity of production management activities on water	**<u>Excellent</u>**: The ratio of maximum/minimum discharge is low (Qmax/Qmin <20) and the physical-chemical water quality is high according to the existing standard **<u>Good</u>**: The ratio of maximum/minimum discharge is low (Qmax/Qmin <20) and the physical-chemical water quality is moderate according to the existing standard **<u>Fair</u>**: The ratio of maximum/minimum discharge is low (Qmax/Qmin <20) and the physical-chemical water quality is poor according to the existing standard **<u>Poor</u>**: The ratio of maximum/minimum discharge is moderate (Qmax/Qmin = 20–50) and the physical-chemical water quality is poor according to the existing standard **<u>Bad</u>**: The ratio of maximum/minimum discharge is high (Qmax/Qmin > 50) and the physical-chemical water quality is poor according to the existing standard

Appendix A (continued)

Indicator	Intensity scale (norm) *)
E1.8 Effectiveness of damage management of forest structure and composition	**Excellent**: SOP (standard operating procedure) for managing damage of the structure and stand/forest composition is adequate and the results are good **Good**: SOP for managing damage of the structure and stand/forest composition is adequate and the results are moderate **Fair**: SOP for managing damage of the structure and stand/forest composition is adequate and the results are poor **Poor**: SOP for managing damage of the structure and stand/forest composition is fairly adequate and the results are poor **Bad**: SOP for managing damage of the structure and stand/forest composition is inadequate and the results are poor
E1.9 Effectiveness of controlling techniques on the impact of production management activities on soil	**Excellent**: SOP for controlling the impact of production management activities on soil is adequate and the results are good **Good**: SOP for controlling the impact of production management activities on soil is adequate and the results are fairly adequate **Fair**: SOP for controlling the impact of production management activities on soil is adequate but the results are poor **Poor**: SOP for controlling the impact of production management activities on soil is fairly adequate but the results are poor **Bad**: SOP for controlling the impact of production management activities on soil is inadequate and the results are poor
E1.10 Effectiveness of controlling techniques on the impact of production management activities on water	**Excellent**: SOP for controlling the impact of production management activities on water is adequate and the results are good **Good**: SOP for controlling the impact of production management activities on water is adequate and the results are fairly good **Fair**: SOP for controlling the impact of production management activities on water is adequate but the results are poor **Poor**: SOP for controlling the impact of production management activities on water is fairly adequate but the results are poor **Bad**: SOP for controlling the impact of production management activities on water is inadequate and the results are poor

Appendix A (continued)

Indicator	Intensity scale (norm) *)
E1.11 Effectiveness of counselling on the importance of forest ecosystem conservation as a life support system, the impact of abundant harvest activities to forest ecosystem, and the importance of endangered/ endemic/protected species conservation	**Excellent**: SOP of counselling is adequate and its results are good **Good**: SOP of counselling is adequate and its results are fairly good **Fair**: SOP of counselling is adequate but its results are poor **Poor**: SOP of counselling is fairly adequate and its results are poor **Bad**: SOP of counselling is inadequate and its results are poor
E2.1 Proportion of protected area that has been stipulated based on consideration of the existence of endangered/endemic/ protected species or unique ecosystem (special area) and/or has been recognized by relevant parties	**Excellent**: Size of the special area which is functioning well and already confirmed and/or recognized by relevant parties is equal to or larger than the total size of actual special area **Good**: Size of the special area which is functioning well and already confirmed and/or recognized by relevant parties is 75–100% of the total size of actual special area **Fair**: Size of the special area which is functioning well and already confirmed and/or recognized by relevant parties is 50–75% of the total size of actual special area **Poor**: Size of the special area which is functioning well and already confirmed and/or recognized by relevant parties is less than 50% (<50%) of the total size of actual special area **Bad**: Size of the special area is more than 50% (>50%) of the total size of actual special area, but it is not functioning well and has not been confirmed and/or recognized by the relevant parties
E2.2 Proportion of well-designed protected area, specifically designed for the survival of endingered/endemic/protected species or protected unique ecosystem that has been delineated in the field	**Excellent**: The realization of boundary delineation of a well-designed special area is equal to the size of the actual special area **Good**: The realization of boundary delineation of a well-designed special area is 75–100% of the size of the actual special area **Fair**: The realization of boundary delineation of a well-designed special area is 50 – 75% of the size of the actual special area **Poor**: The realization of boundary delineation of a well-designed special area is 25 – 50% of the size of the actual special area **Bad**: The realization of boundary delineation of a well-designed special area is less than 25% (< 25%) of the size of the actual special area
E2.3 Damage intensity to endangered/ endemic/protected species in the special areas	**Excellent**: No damage to endangered/endemic/protected species in the special area **Good**: The degree of damage to the endemic/endangered/protected species in the special area is low and its controlling efforts are adequate **Fair**: The degree of damage to the endemic/endangered/protected species in the special area is low and its controlling efforts are less adequate

Appendix A (continued)

Indicator	Intensity scale (norm) *)
E2.3	**Poor**: The degree of damage to the endemic/endangered/protected species in the special area is high and its controlling efforts are adequate **Bad**: The degree of damage to the endemic/endangered/protected species in the special area is high and its controlling efforts are less adequate
E2.4 Condition of endangered/ endemic/protec-ted species in the special areas	**Excellent**: The abundance of endangered/endemic/protected plant and animal species in the special area is bigger or equal to those in the virgin forest, and even bigger than those in the old logged-over area (>20 yrs.). **Good**: The abundance of endangered/endemic/protected flora species in the special area is 90–100% of those in the virgin forest and the old logged-over area, and the abundance of endangered/endemic/protected wild animal species in special area is 80–100% of those in the virgin forest and the old logged-over area **Fair**: The abundance of endangered/endemic/protected flora species in the special area is 70–90% of those in the virgin forest and the old logged-over area, and the abundance of endangered/endemic/protected wild animal species in special area is 60–80% of those in the virgin forest and the old logged-over area **Poor**: The abundance of endangered/endemic/protected flora species in the special area is 60–70% of those in the virgin forest and the old logged-over area, and the abundance of endangered/endemic/protected wild animal species in special area is 40–60% of those in the virgin forest and the old logged-over area **Bad**: The abundance of endangered/endemic/protected flora species in the special area is 60% of those in the virgin forest and the old logged-over area, and the abundance of endangered/endemic/protected wild animal species in special area is <40% of those in the virgin forest and the old logged-over area
E2.5 Impact intensity of production management activities towards endangered/endemic/protected plant species and their habitat	**Excellent**: The community similarity index between the old logged-over area and the virgin forest is greater than 50%, and the amount of endemic/endangered/protected plant species in the old logged-over area is greater than or equal to those found in the virgin forest **Good**: The community similarity index between the old logged-over area and the virgin forest is greater than 50%, and the amount of endemic/endangered/protected plant species in the old logged-over area is >80 % than those found in the virgin forest **Fair**: The community similarity index between the old logged-over area and the virgin forest is greater than 50%, and the amount of endemic/endangered/protected plant species in the old Logged over area is <80% than those found in the virgin forest **Poor**: The community similarity index between the old logged-over area and the virgin forest is <25%, and the amount of endemic/endangered/protected plant species in the old logged-over area is >80 % than those found in the virgin forest **Bad**: The community similarity index between the old logged-over area and the virgin forest is <25%, and the amount of endemic/endangered/protected plant species in the old logged-over area is <80% than those found in the virgin forest

Appendix A (continued)

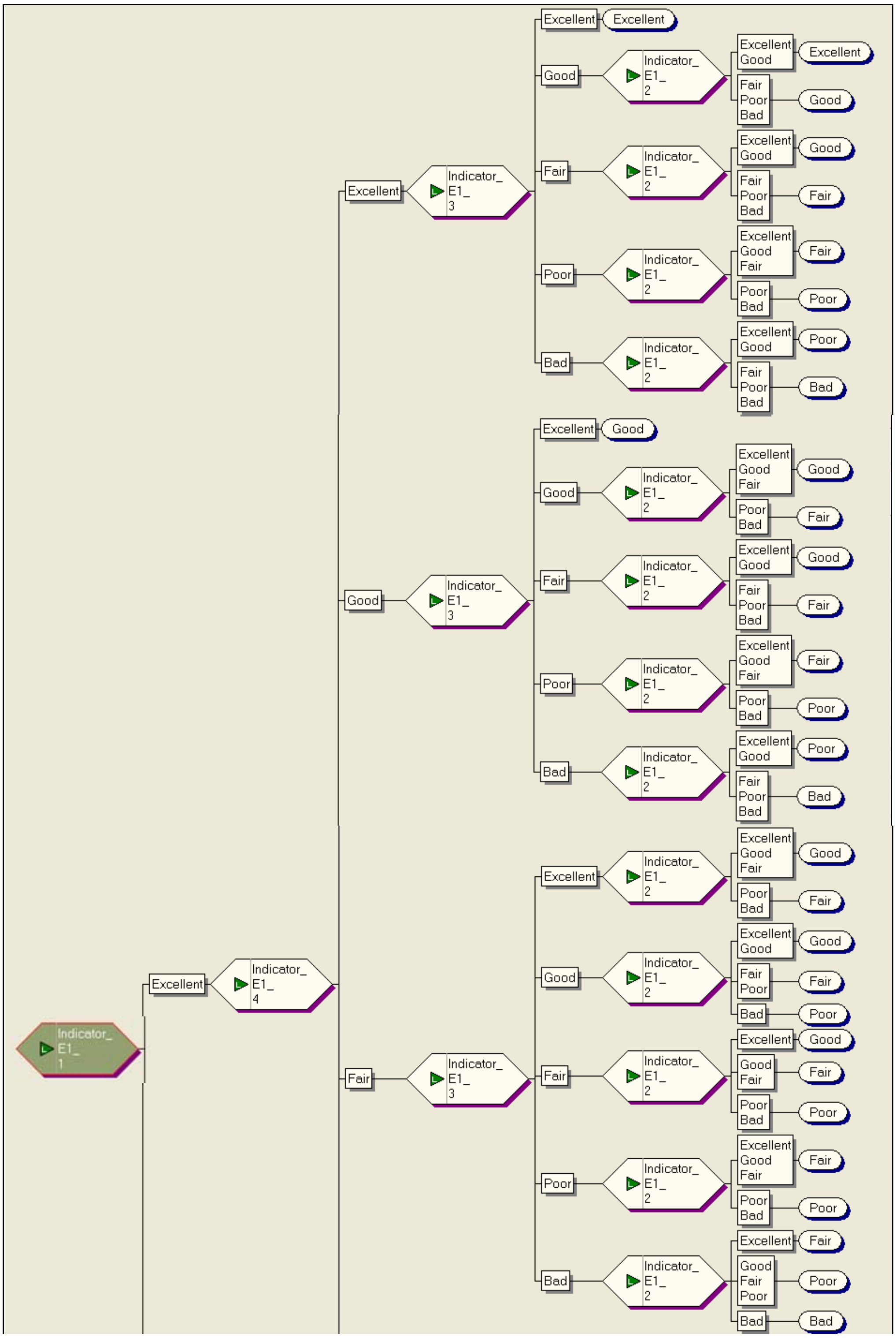
Indicator	Intensity scale (norm) *)
E2.6 Impact intensity of production management activities towards endangered/endemic/protected wild animal species and their habitat	**Excellent**: The community similarity index between the old logged-over area and the virgin forest is greater than 50%, and the amount of endemic/endangered/protected wild animal species in the old logged-over area is greater than or equal to those found in the virgin forest, and the degree of habitat fragmentation in the old logged-over area is <15% **Good**: The community similarity index between the old logged-over area and the virgin forest is greater than 50%, and the amount of endemic/endangered/protected wild animal species in the old logged-over area is greater than or equal to those found in the virgin forest, and the degree of habitat fragmentation in the old logged-over area is 15–25% **Fair**: The community similarity index between the old logged-over area and the virgin forest is greater than 50%, and the amount of endemic/endangered/protected wild animal species in the old logged-over area is greater than or equal to those found in the virgin forest, and the degree of habitat fragmentation in the old logged-over area is 25%. **Poor**: The community similarity index between the old logged-over area and the virgin forest is greater than 50%, and the amount of endemic/endangered/protected wild animal species in the old logged over area is >80% of those found in the virgin forest, and the degree of habitat fragmentation in the old logged-over area is >25% **Bad**: The community similarity index between the old logged-over area and the virgin forest is greater than 50%, and the amount of endemic/endangered/protected wild animal species in the old logged-over area is <80% of those found in the virgin forest, and the degree of habitat fragmentation in the old logged over area is >25%
E2.7 Security of endangered/endemic/protected plant species and their habitat	**Excellent**: SOP (standard operating procedure) for the protection of endemic/endangered/protected plant species and their habitat is adequate, and the protection is successful **Good**: SOP for the protection of endemic/endangered/protected plant species and their habitat is adequate, an d the protection is fairly successful **Poor**: SOP for the protection of endemic/endangered/protected plant species and their habitat is fairly adequate , but the protection is unsuccessful **Bad**: SOP for the protection of endemic/endangered/protected plant species and their habitat is inadequate, and the protection is unsuccessful
E2.8 Security of endangered/endemic/protected wild animal species and their habitat	**Excellent**: SOP (standard operating procedure) for the protection of endemic/endangered/protected wild animals and their habitat is adequate, and the protection is successful. **Good**: SOP for the protection of endemic/endangered/protected wild animals and their habitat is adequate, and the protection is fairly successful **Fair**: SOP for the protection of endemic/endangered/protected wild animals and their habitat is adequate, but the protection is unsuccessful **Poor**: SOP for the protection of endemic/endangered/protected wild animals and their habitat is fairly adequate, and the protection is unsuccessful **Bad**: SOP for the protection of endemic/endangered/protected wild animals and their habitat is inadequate and the protection is unsuccessful

**) In the LEI system there are some other definitions of the intensity scales, see LEI (2000) for the complete definitions*

Appendix B. The rule base used in the FRB-1 and FRB-2 models to assess sustainability of ecological functions using the LEI system

B.1. The rule bases used for aggregating various C&I components under the stability of ecosystem criteria

B.1.1. Area Management (AM-1)



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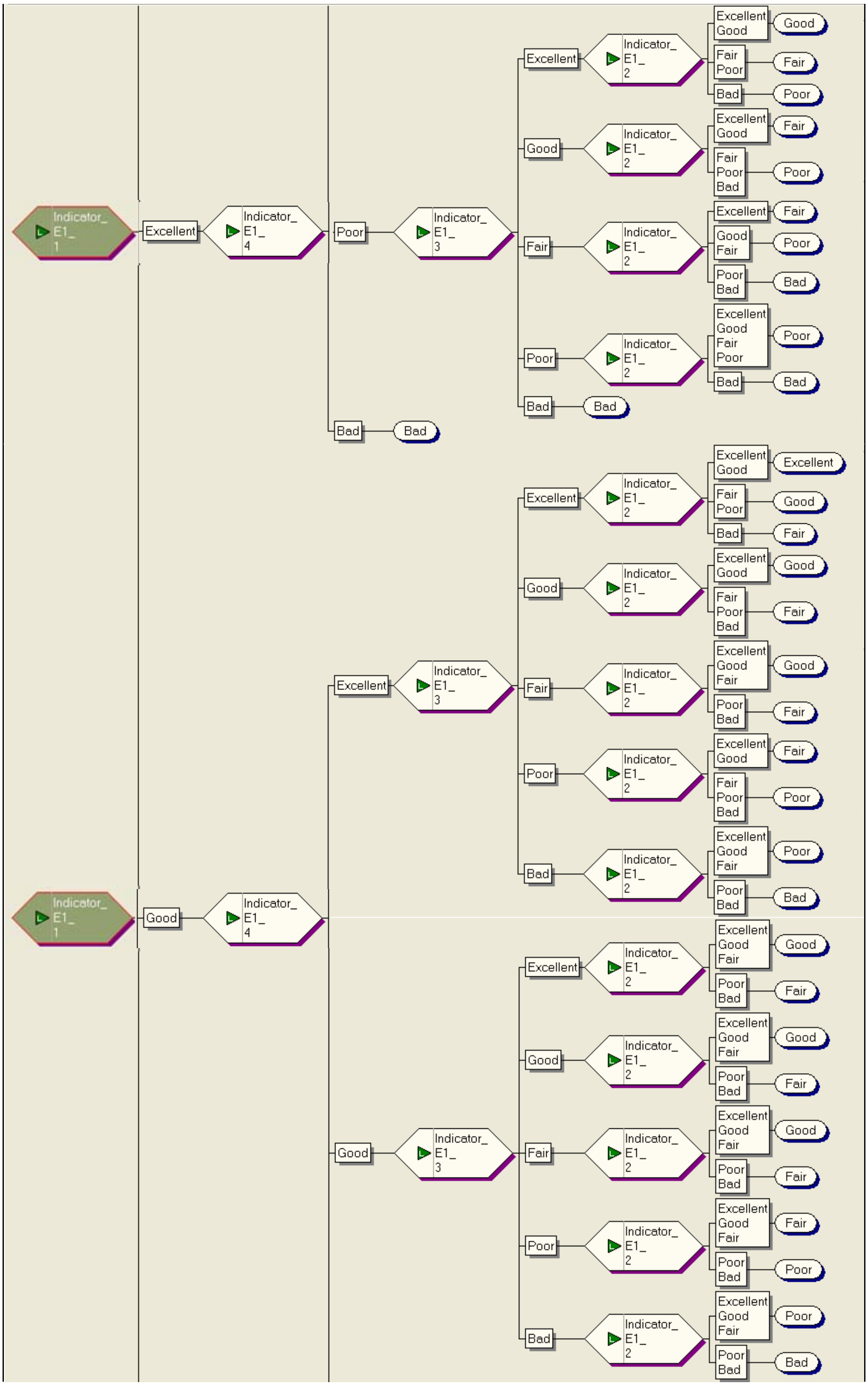

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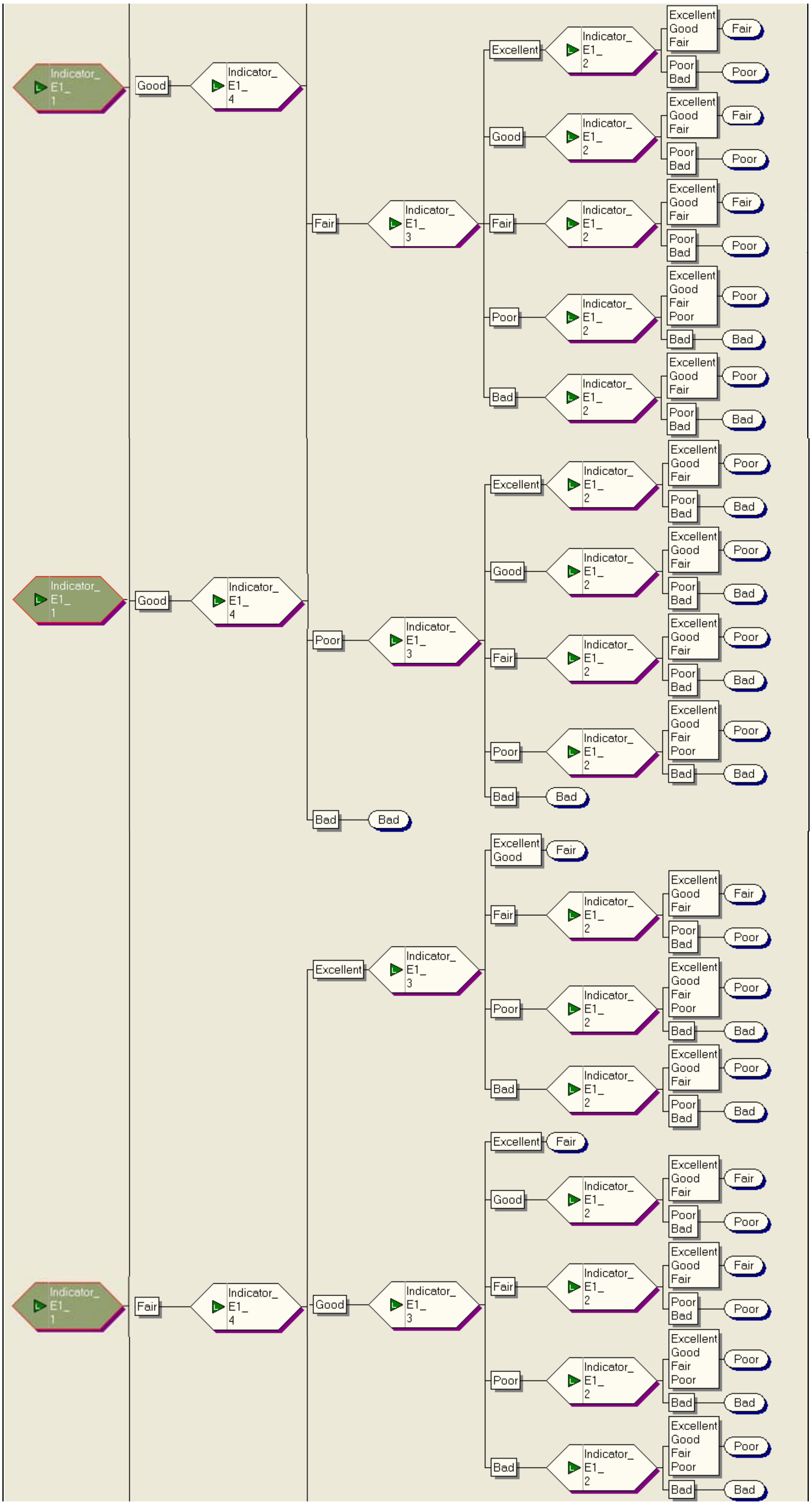

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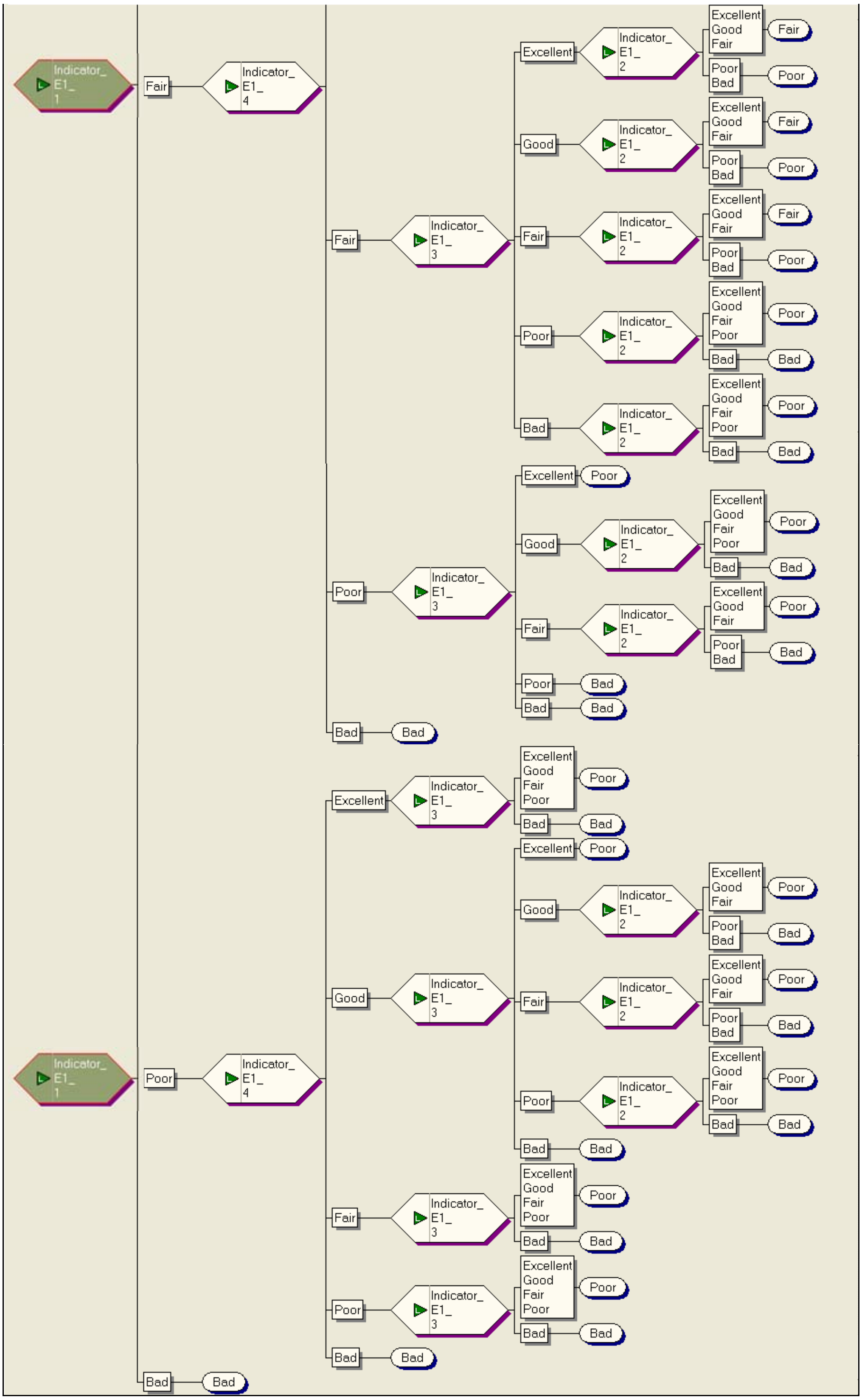

Indicator_ E1_ 1
Fair
Indicator_ E1_ 4
Fair
Indicator_ E1_ 3
Excellent
Indicator_ E1_ 2
Excellent Good Fair
Fair
Poor Bad
Poor
Good
Indicator_ E1_ 2
Excellent Good Fair
Fair
Poor Bad
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Indicator_ E1_ 2
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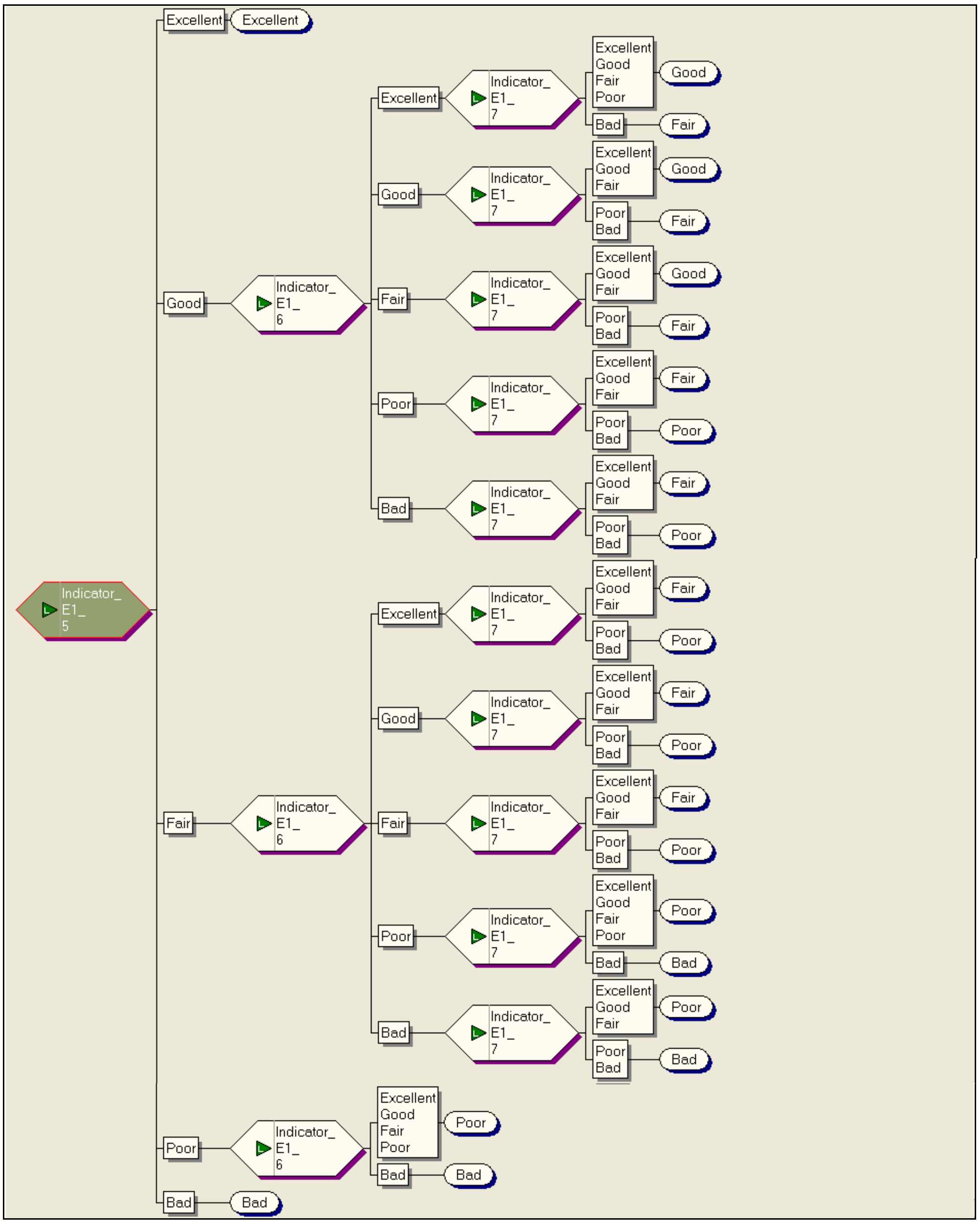
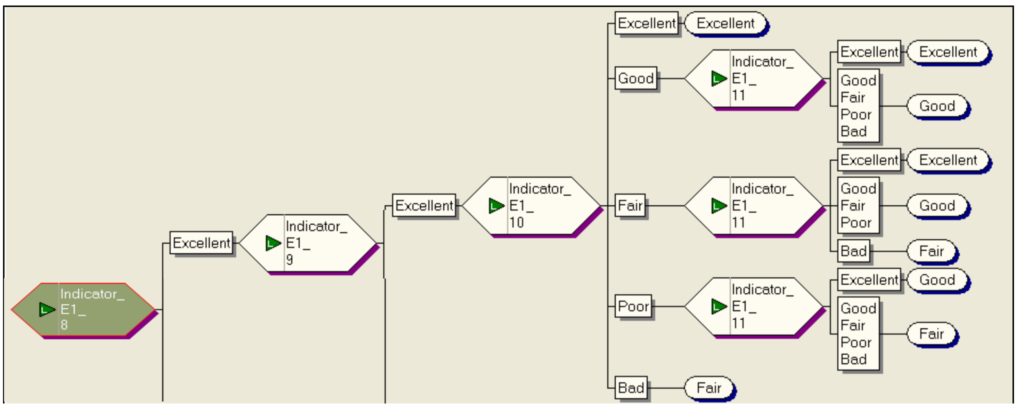
B.1.2. Production Management (PM-1)



B.1.3. Environmental Management (EM-1)



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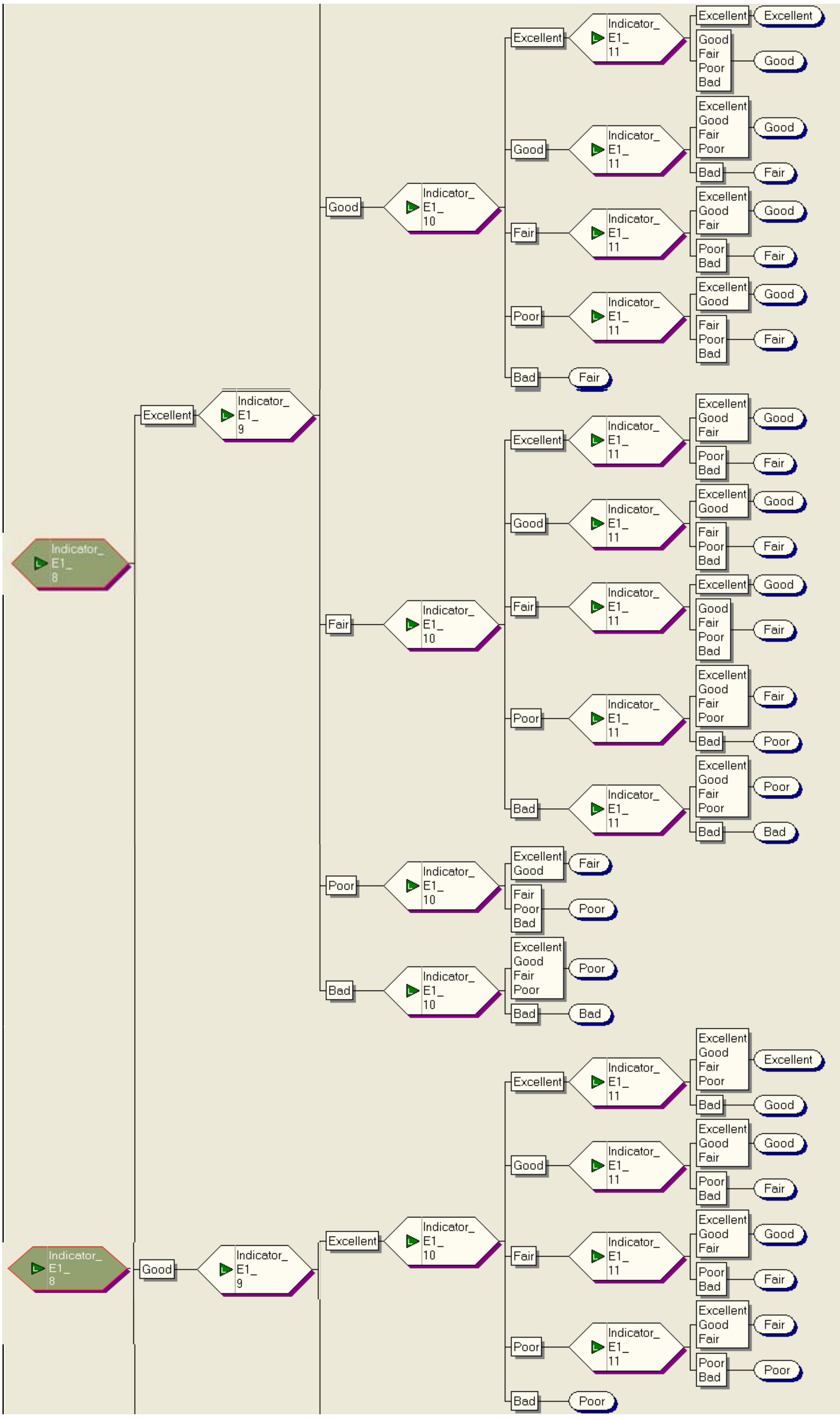

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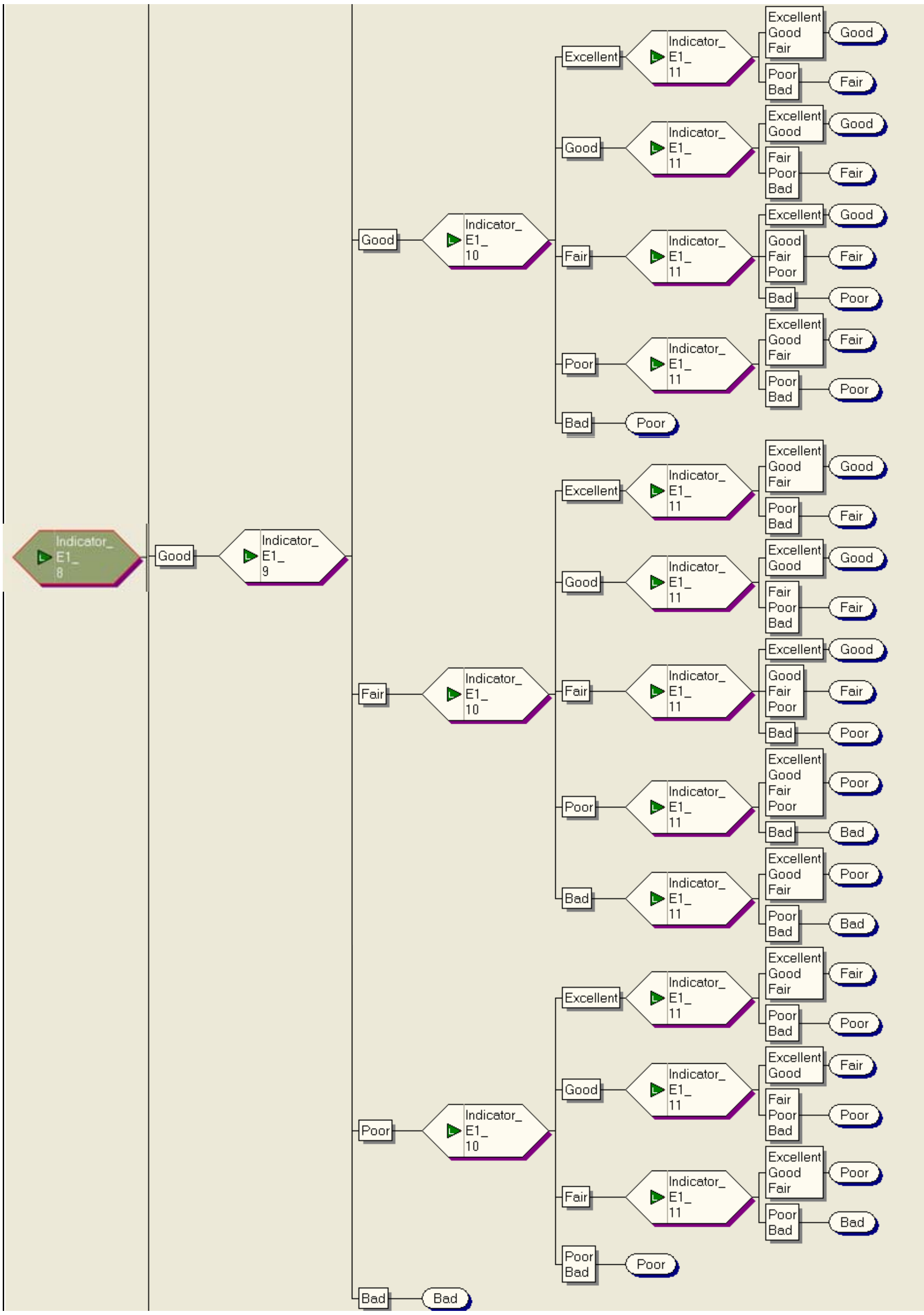

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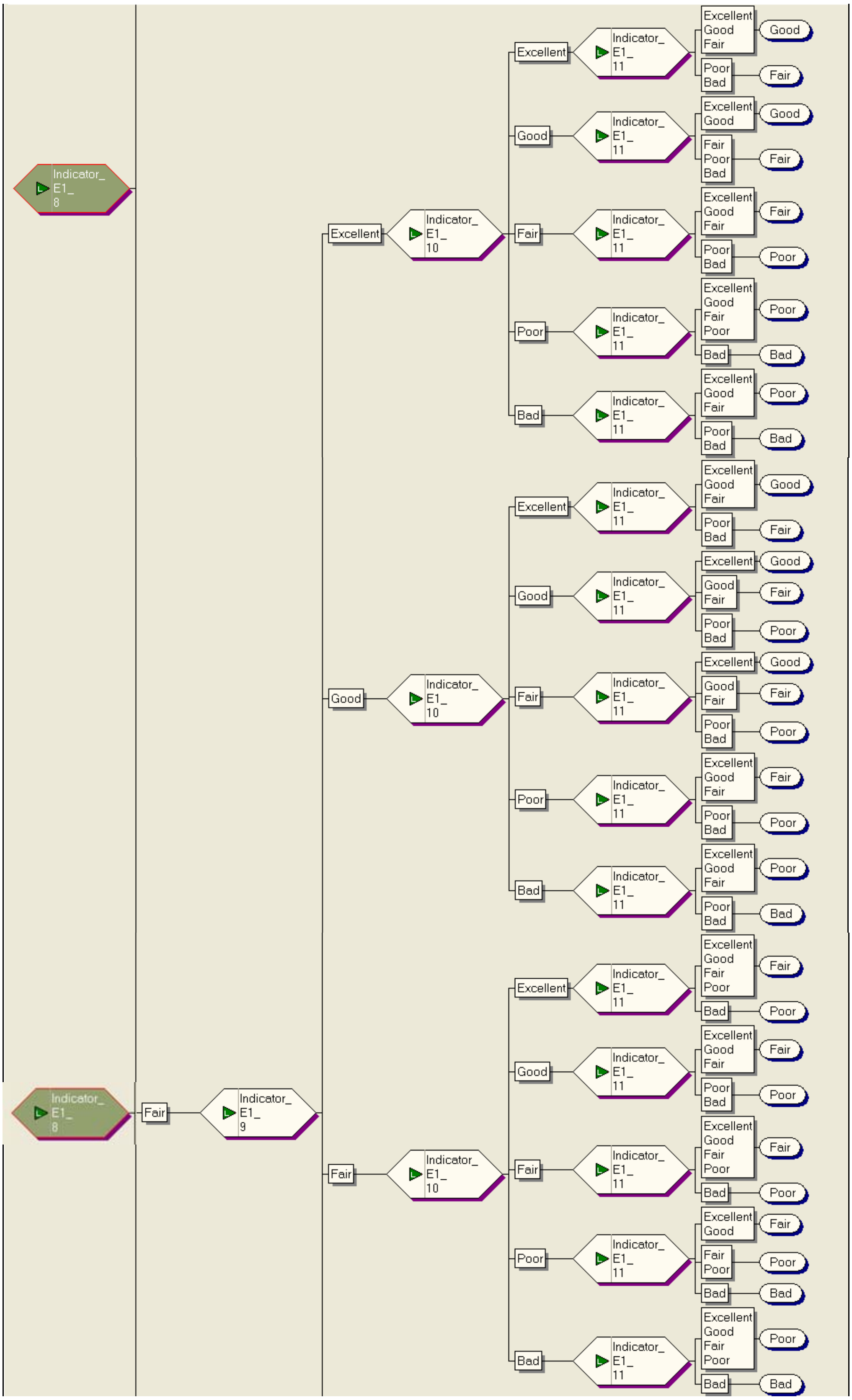

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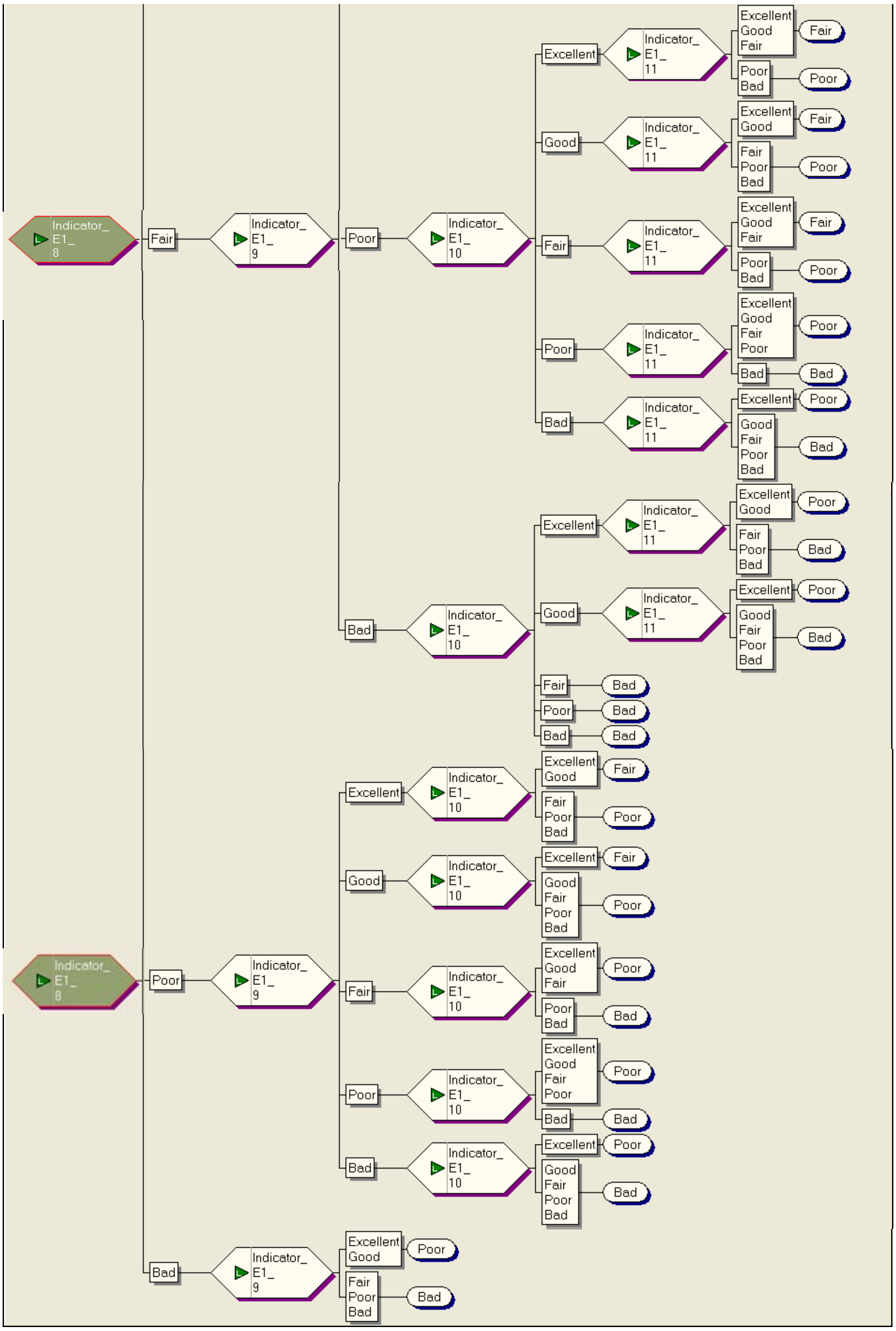

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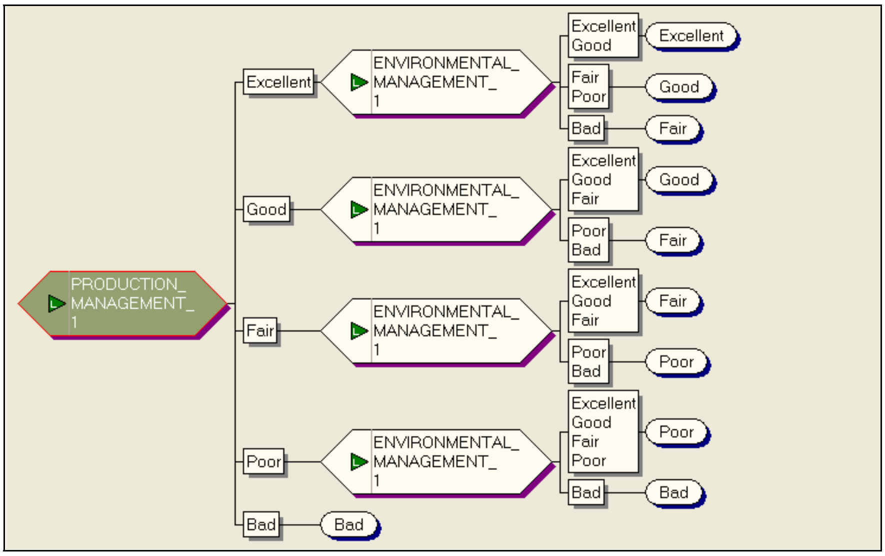
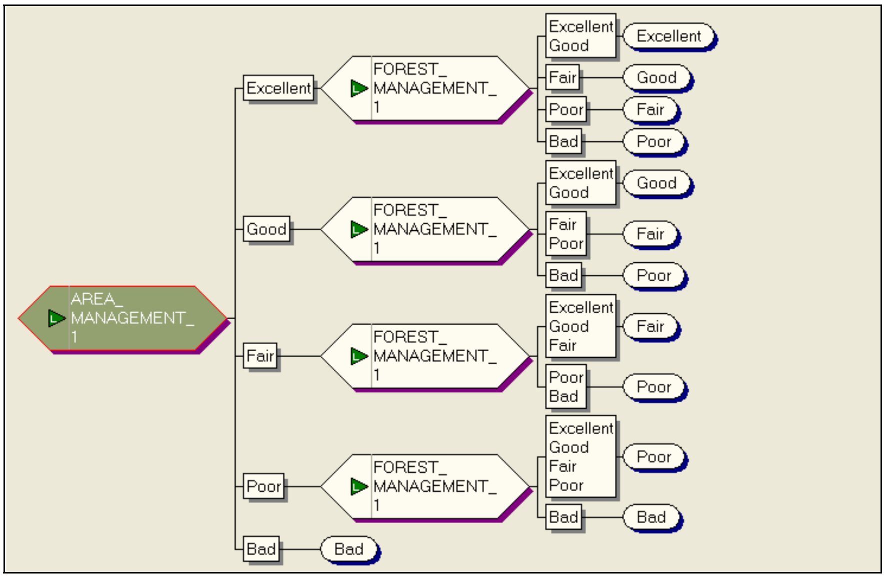
B.1.4. Forest Management (FM-1)

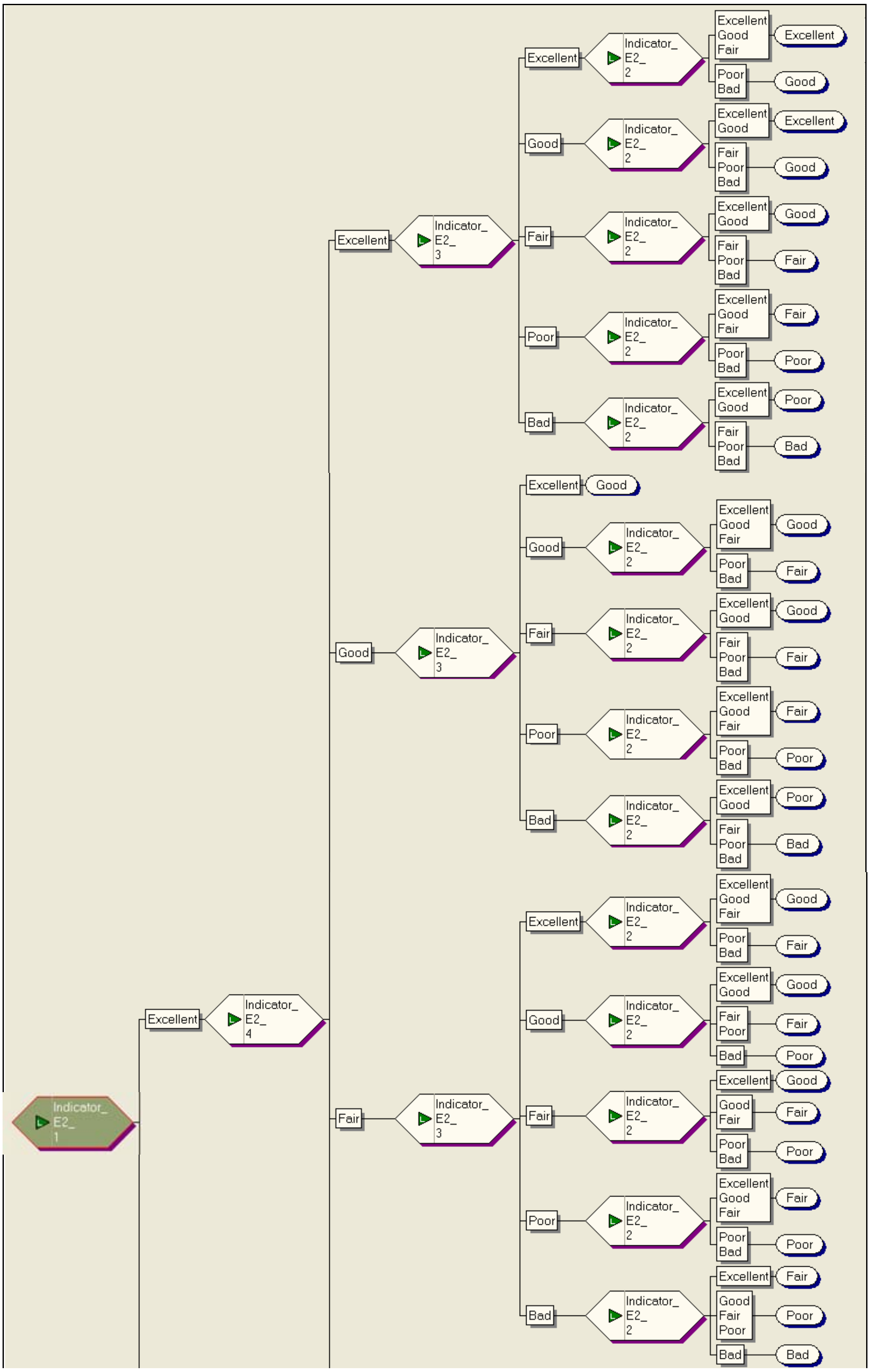


B.1.5. Stability of ecosystem (SE-1)



B.2. The rule bases used for aggregating various C&I components under the survival of endangered species criteria

B.2.1. Area Management (AM-2)



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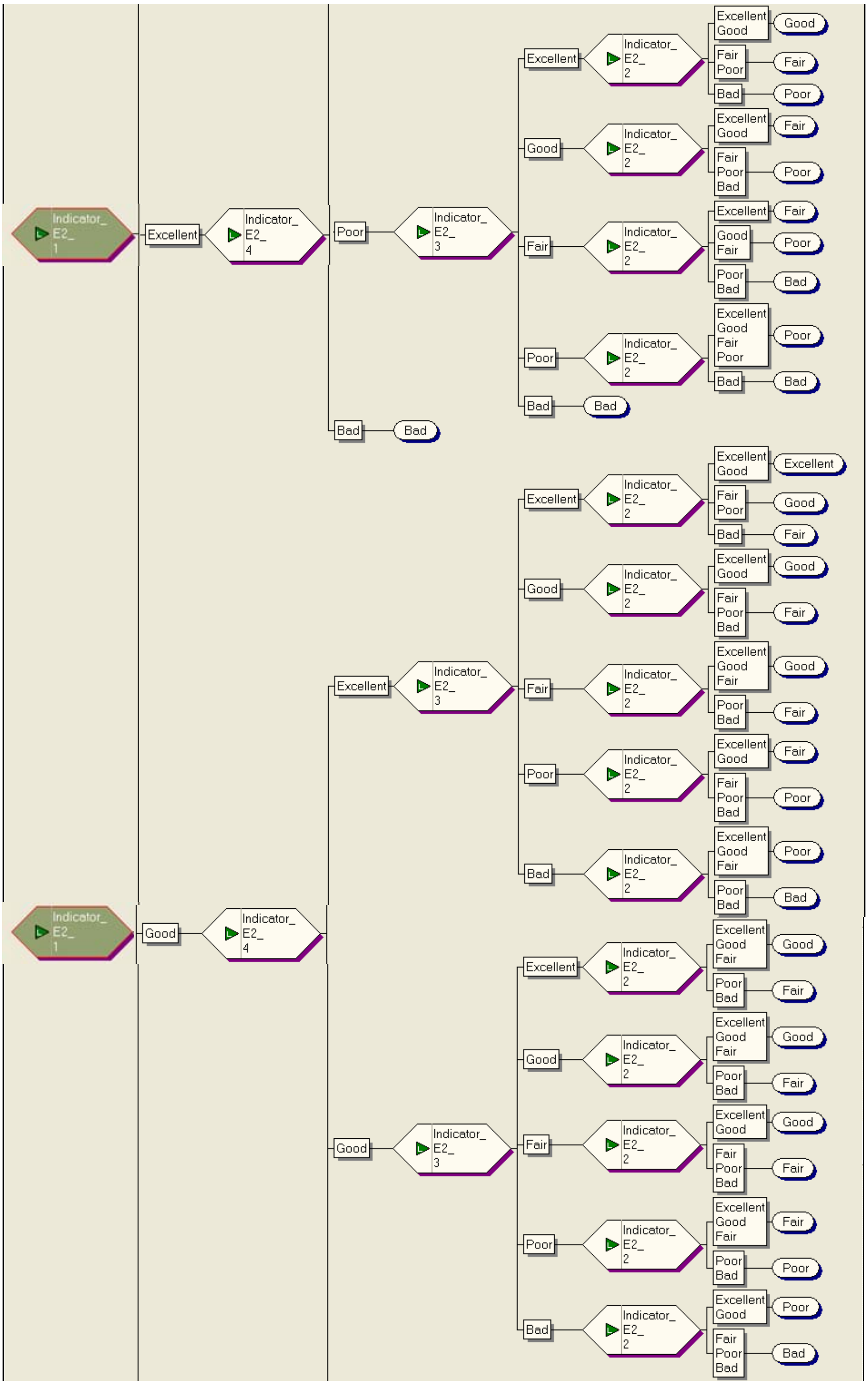

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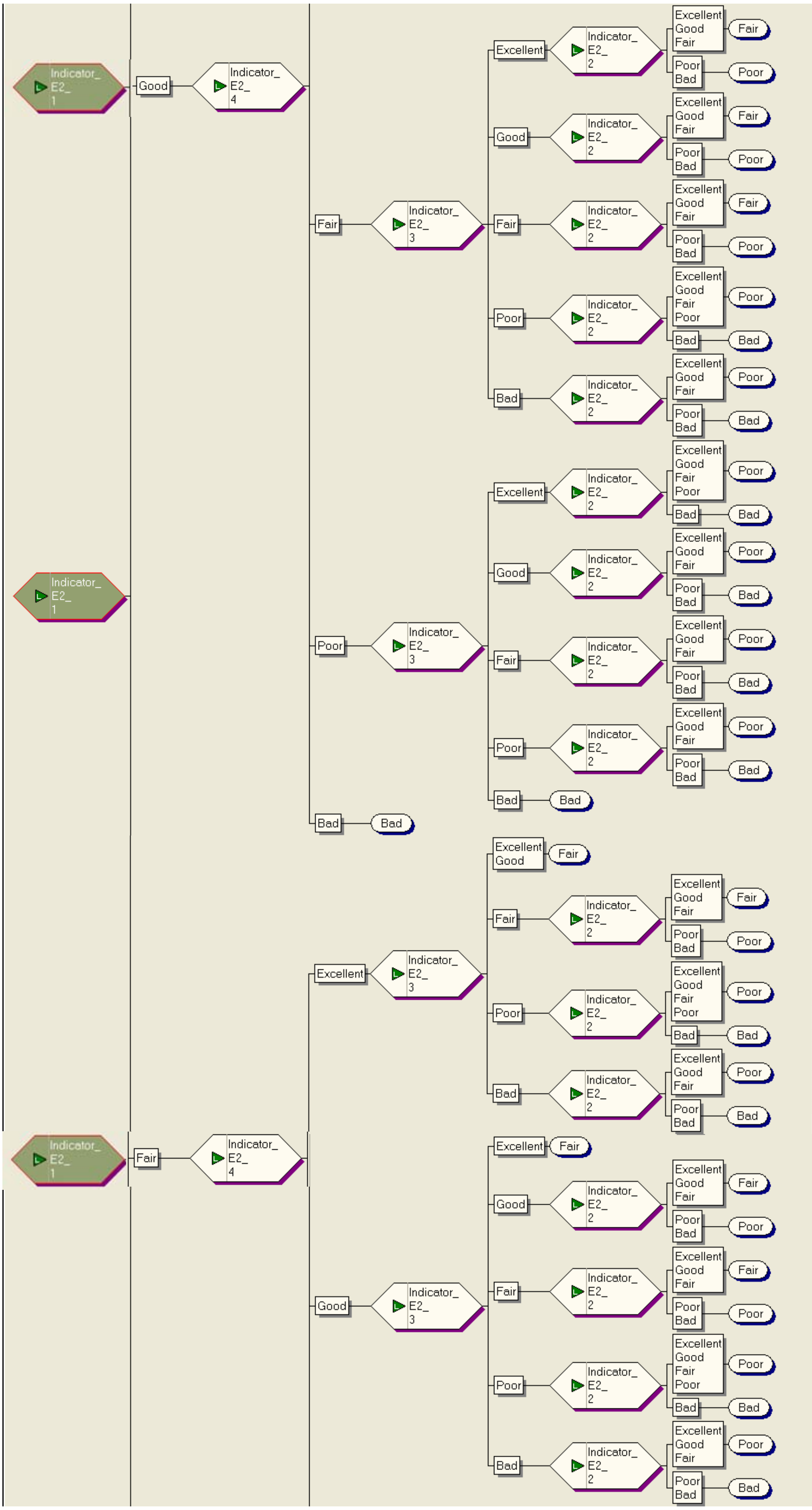

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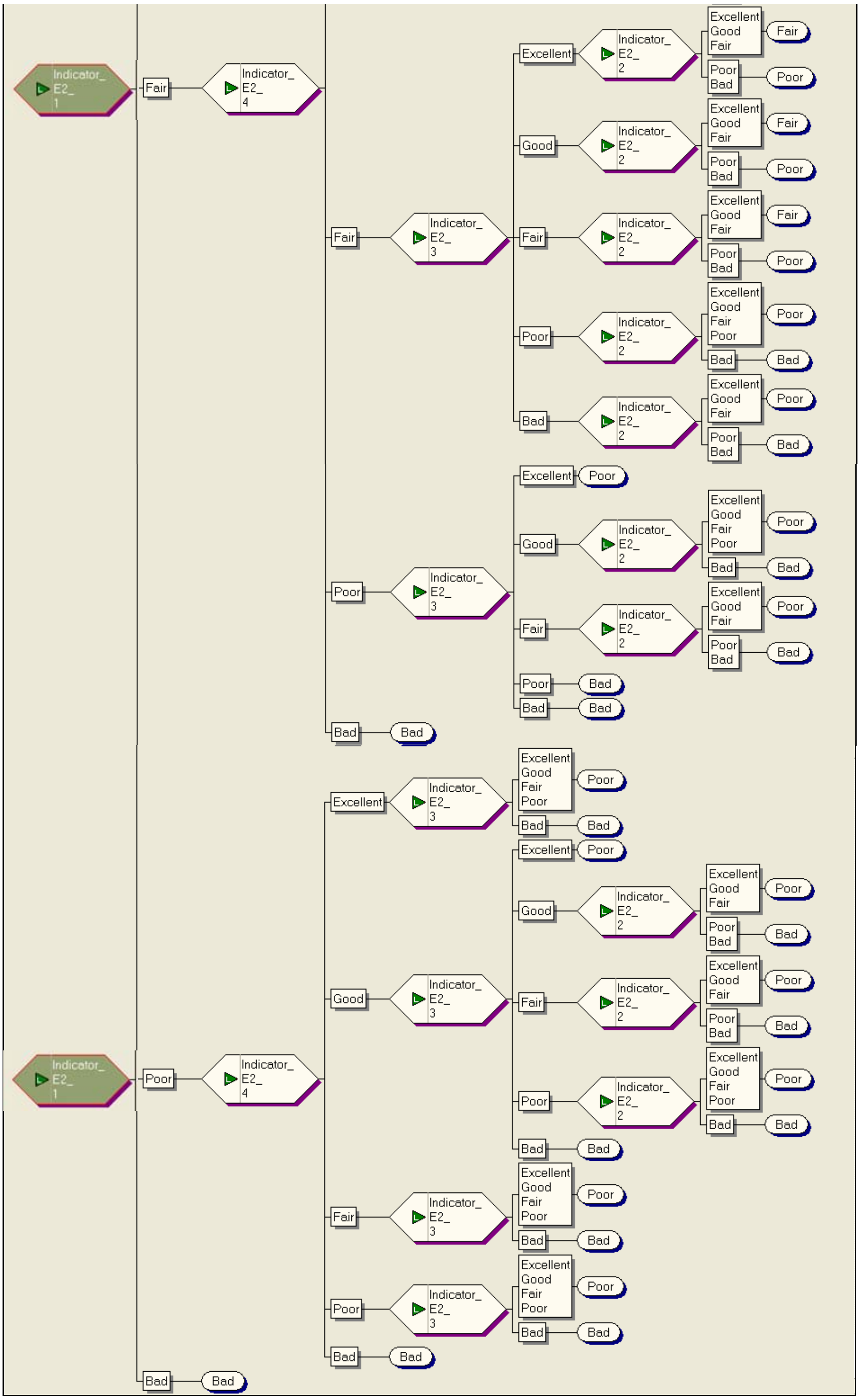
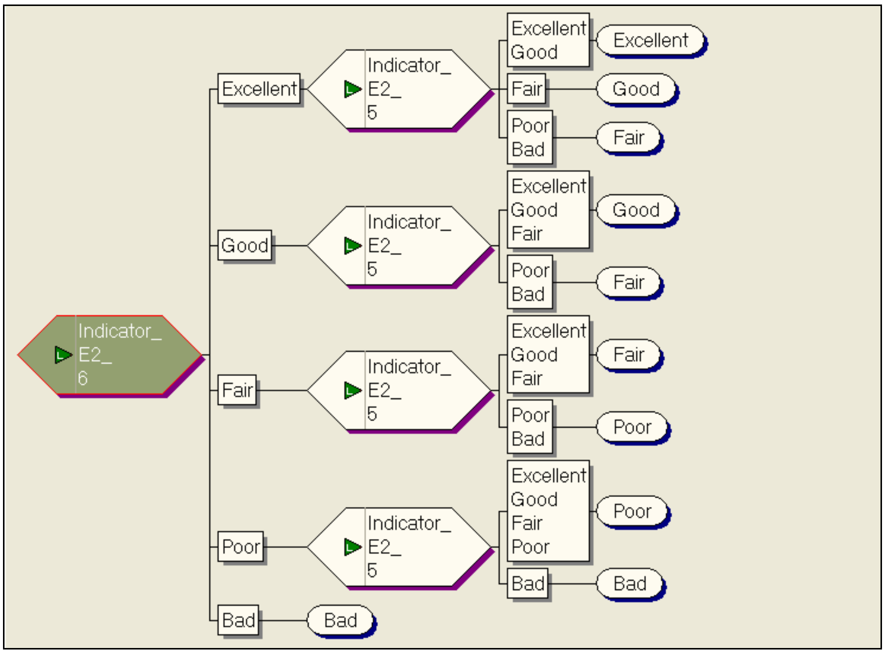
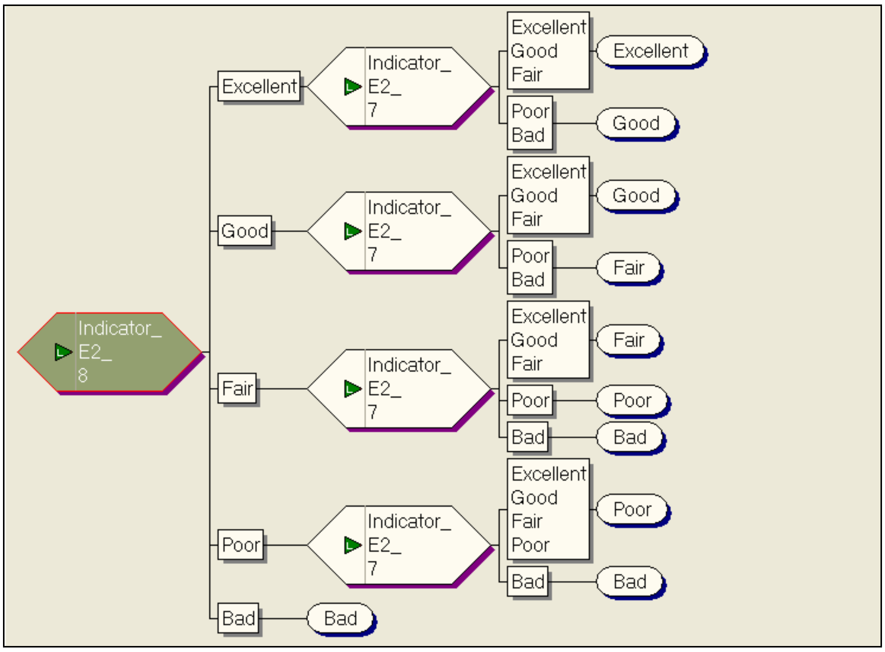


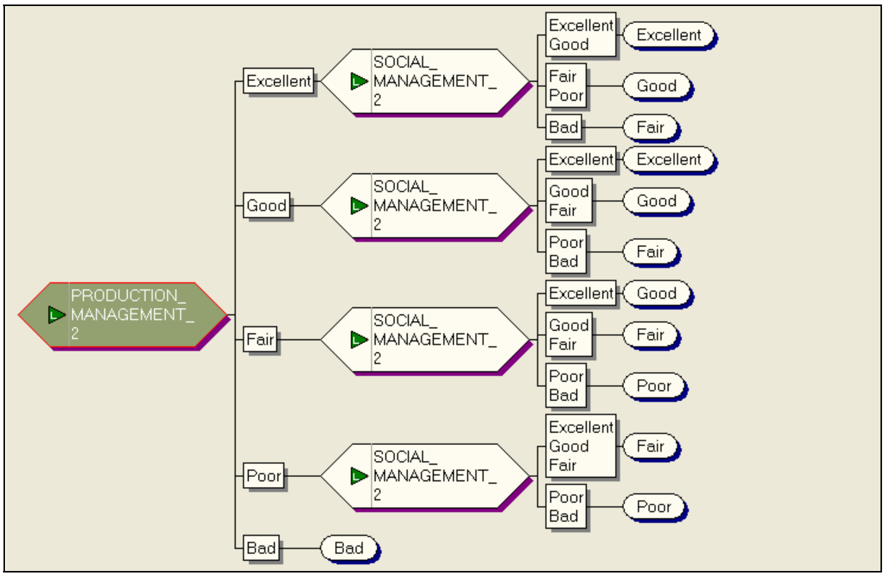
B.2.2. Production Management (PM-2)



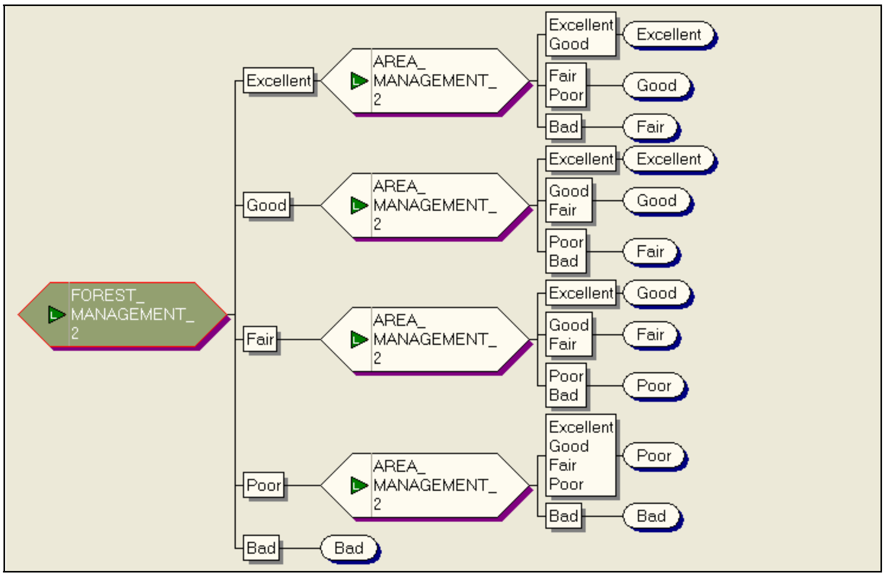
B.2.3. Social Management (SM-2)



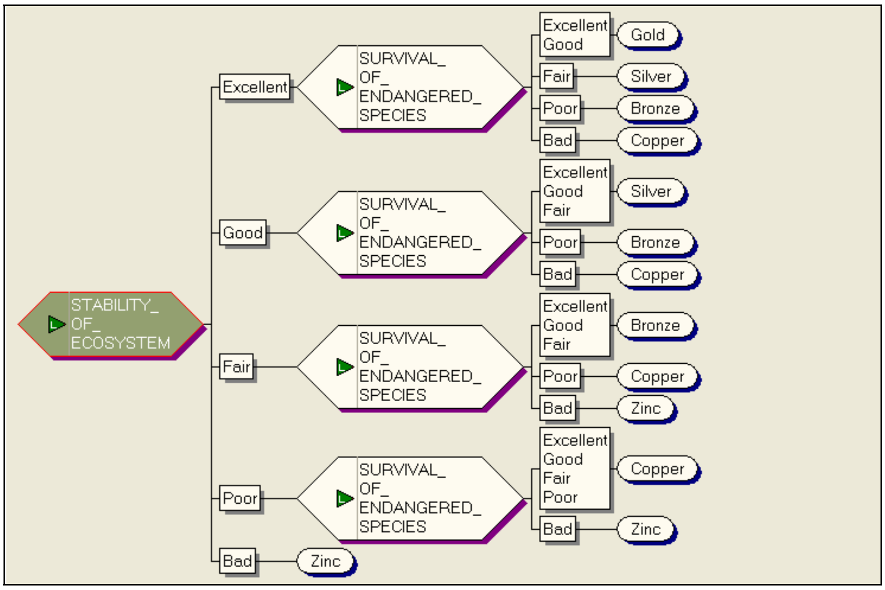
B.2.4. Forest Management (FM-2)



B.2.5. Survival of endangered species (SS-2)



B.3. Principle of sustainability of ecological function



Appendix C. Description of the selected verifiers of ecological indicators of SFM in the LEI system (based on the expert knowledge and the LEI's documents)

Indicator	Selected verifier	Possible definition of verifier*)
E1.1 Proportion of a well-functioning protected area to the total area that should be protected and has already been stipulated and/or acknowledged by relevant parties	E1.1.1 Size and condition of steep slope area	**Excellent**: Size of steep slope area for the protected area is equal or larger than its total size, and it has good condition **Fair**: Size of steep slope area for the protected area is 50-75% of its total size, and it has moderate condition **Bad**: Size of steep slope area for the protected area is <25% of its total size, and it has bad condition
	E1.1.2 Size and condition of biodiversity conservation area	**Excellent**: Size of biodiversity conservation area is equal or larger than its total size of biodiversity conservation area that should be allocated for the protected area, and it has good condition **Fair**: Size of biodiversity conservation area is 50-75% of the total size of biodiversity conservation area that should be allocated for the protected area, and it has moderate condition **Bad**: Size of biodiversity conservation area is <25% of the total size of biodiversity conservation area that should be allocated for the protected area, and it has bad condition
	E1.1.3 Size and condition of river front	**Excellent**: Size of river front for the protected area is equal or larger than its total size, and it has good condition **Fair**: Size of river front for the protected area is 50-75% of its total size, and it has moderate condition **Bad**: Size of river front for the protected area is <25% of its total size, and it has bad condition
E1.2 Proportion of a well-managed protected area to the total size that should be protected and already delineated in the field	E1.2.1 Delineation of a well-managed steep slope area	**Excellent**: Delineation of steep slope area boundaries is equal to its total boundary **Fair**: Delineation of steep slope area boundaries is 50-75% of its total boundary **Bad**: Delineation of steep slope area boundaries is <25% of its total boundary
	E1.2.2 Delineation of a well-managed river front	**Excellent**: Delineation of river front boundaries is equal to its total boundary **Fair**: Delineation of river front boundaries is 50-75% of its total boundary **Bad**: Delineation of river front boundaries is <25% of its total boundary
	E1.2.3 Realization and quality of the boundaries	**Excellent**: Realization of delineation of the protected area boundaries is equal to its total boundary, and its quality is good **Fair**: Realization of delineation of the protected area boundaries is 50-75% of its total boundary, and its quality is moderate **Bad**: Realization of delineation of the protected area boundaries is <25% of its total boundary, and its quality is bad

Appendix C (continued)

Indicator	Selected verifier	Possible definition of verifier*)
E1.3 Intensity of damage in the protected areas, including fire hazards	E1.3.1 Size and type of damaged protected area	**Excellent**: The size of damaged area is <10% of the total protected area **Fair**: The size of damaged area is 10-25% of the total protected area **Bad**: The size of damaged area is >50% of the total protected area
	E1.3.2 Condition of damaged protected area	**Excellent**: There is a low degree of damage **Fair**: There is a moderate degree of damage **Bad**: There is a high degree of damage
	E1.3.3 SOP for forest fire prevention	**Excellent**: SOP for forest fire prevention is available and the control efforts are adequate **Fair**: SOP for forest fire prevention is available but the control efforts fairly adequate **Bad**: SOP for forest fire prevention is not available
E1.4 Condition of flora and/or fauna species diversity in protected area in various forest formations/types within management units	E1.4.1 Flora and fauna diversity in protected area	**Excellent**: Diversity of flora and fauna in protected area is >80% of those in virgin forest **Fair**: Diversity of flora and fauna in protected area is 60–80% of those in virgin forest **Bad**: Diversity of flora and fauna in protected area is <60% of those in virgin forest
	E1.4.2 Flora and fauna diversity in virgin forest	**Excellent**: Diversity of flora and fauna in virgin forest is >80% of those in the existing standard **Fair**: Diversity of flora and fauna in virgin forest is 60–80% of those in the existing standard **Bad**: Diversity of flora and fauna in virgin forest is <60% of those in the existing standard
	E1.4.3 Flora and fauna diversity in logged-over area	**Excellent**: Diversity of flora and fauna in logged-over area is >80% of those in virgin forest **Fair**: Diversity of flora and fauna in logged-over area is 60–80% of those in virgin forest **Bad**: Diversity of flora and fauna in logged-over area is <60% of those in virgin forest
E1.5 Damage intensity of forest structure and plant species composition	E1.5.1 Level of similarities between logged-over area and virgin forest	**Excellent**: Index of similarity between logged-over area and virgin forest is >50% **Fair**: Index of similarity between logged-over area and virgin forest is 25–50% **Bad**: Index of similarity between logged-over area and virgin forest is <25%

Appendix C (continued)

Indicator	Selected verifier	Possible definition of verifier*)
E1.5	E1.5.2 Structure and composition of plant species in logged-over area	**Excellent**: Number and diversity of endangered plant species in logged-over area are >75% of those in virgin forest **Fair**: Number and diversity of endangered plant species in logged-over area are 50–75% of those in virgin forest **Bad**: Number and diversity of endangered plant species in logged-over area are >50% of those in virgin forest
	E1.5.3 Structure and composition of plant species in virgin forest	**Excellent**: Number and diversity of endangered plant species in virgin forest are >75% of those in the existing standard **Fair**: Number and diversity of endangered plant species virgin forest are 50–75% of those in the existing standard **Bad**: Number and diversity of endangered plant species virgin forest are >50% of those in the existing standard
E1.6 Impact intensity of production management activities on soil	E1.6.1 Erosion level in logged-over area	**Excellent**: Erosion hazard index is low (IBE<1) **Fair**: Erosion hazard index is moderate (IBE=1) **Bad**: Erosion hazard index is high (IBE>1)
	E1.6.2 Concentration of suspended soil	**Excellent**: Concentration of suspended soil in water bodies is low (<100 mg/l) **Fair**: Concentration of suspended soil in water bodies is moderate (100-250 mg/l) **Bad**: Concentration of suspended soil in water bodies is high (>250 mg/l)
E1.7 Impact intensity of production management activities on water	E1.7.1 Quality of river or other water bodies	**Excellent**: The physical and chemical water quality is high according to the existing standard **Fair**: The physical and chemical water quality is moderate according to the existing standard **Bad**: The physical and chemical water quality is poor according to the existing standard
	E1.7.2 Fluctuation of water discharge	**Excellent**: Ratio of maximum/minimum discharge is low (Qmax/Qmin < 20) **Fair**: Ratio of maximum/minimum discharge is moderate (Qmax/Qmin = 20–50) **Bad**: Ratio of maximum/minimum discharge is high (Qmax/Qmin >50)
E1.8 Effectiveness of damage management of forest structure and composition	E1.8.1 Quality of residual stand species	**Excellent**: The quality of residual stands is good **Fair**: The quality of residual stands is moderate **Bad**: The quality of residual stand is poor
	E1.8.2 SOP for timber harvesting	**Excellent**: SOP (standard operating procedure) for managing damages is adequate **Fair**: SOP for managing damages is fairly adequate **Bad**: SOP for managing damages is inadequate

Appendix C (continued)

Indicator	Selected verifier	Possible definition of verifier*)
E1.9 Effectiveness of controlling techniques on the impact of production management activities on soil	E1.9.1 Activity of soil conservation in logged-over area	**Excellent**: The results of soil conservation are good **Fair**: The results of soil conservation are moderate **Bad**: The results of soil conservation are poor
	E1.9.2 SOP for impact controlling on soil	**Excellent**: SOP (standard operating procedure) for controlling the impact on soil is adequate **Fair**: SOP for controlling the impact on soil is fairly adequate **Bad**: SOP for controlling the impact on soil is inadequate
E1.10 Effectiveness of controlling techniques on the impact of production management activities on water	E1.10.1 Quantity and quality of water	**Excellent**: There is high improvement in the quantity and quality of water **Fair**: There is moderate improvement in the quantity and quality of water **Bad**: There is no improvement in the quantity and quality of water
	E1.10.2 SOP for impact controlling on water	**Excellent**: SOP (standard operating procedure) for controlling the impact on water is adequate **Fair**: SOP for controlling the impact on water is fairly adequate **Bad**: SOP for controlling the impact on water is inadequate
E1.11 Effectiveness of counselling on the importance of forest ecosystem conservation as a life support system, the impact of abundant harvest activities to forest ecosystem, and the importance of endangered/endemic/protected species conservation	E1.11.1 Community understanding on forest preservation	**Excellent**: The communities have a good understanding on forest preservation **Fair**: The communities have a moderate understanding on forest preservation **Bad**: The communities have a poor understanding on forest preservation
	E1.11.2 Frequency of counselling	**Excellent**: The counselling is conducted frequently (e.g. at least once per 2 weeks) **Fair**: The counselling is conducted occasionally **Bad**: There is no counselling
	E1.11.3 SOP for counselling	**Excellent**: SOP (standard operating procedure) for counselling is adequate to improve the community understanding on forest preservation **Fair**: SOP for counselling is fairly adequate to improve the community understanding on forest preservation **Bad**: SOP for counselling is fairly adequate to improve the community understanding on forest preservation

Appendix C (continued)

Indicator	Selected verifier	Possible definition of verifier*)
E2.1 Proportion of protected area that has been stipulated based on consideration of the existence of endangered/ endemic/ protected species or unique ecosystem (special area) and/or has been recognized by relevant parties	E2.1.1 Size and condition of stipulated biodiversity conservation area	**<u>Excellent</u>**: Size of stipulated conservation area is >75% of the total protected area and **<u>Fair</u>**: Size of stipulated conservation area is 50–75% of the total protected area **<u>Bad</u>**: Size of stipulated conservation area is <50% of the total protected area
	E2.1.2 Size and condition of stipulated animal corridor	**<u>Excellent</u>**: Size of stipulated animal corridor is >75% of the total protected area and **<u>Fair</u>**: Size of stipulated animal corridor is 50–75% of the total protected area **<u>Bad</u>**: Size of stipulated animal corridor is <50% of the total protected area
	E2.1.3 Size and condition of stipulated other special areas	**<u>Excellent</u>**: Size of stipulated special area is >75% of the total protected area and **<u>Fair</u>**: Size of stipulated special area is 50–75% of the total protected area **<u>Bad</u>**: Size of stipulated special area is <50% of the total protected area
E2.2 Proportion of well-designed protected area, specifically designed for the survival of endangered/ endemic/protected species or protected unique ecosystem that has been delineated in the field	E2.2.1 Delineation of the stipulated biodiversity conservation area	**<u>Excellent</u>**: Delineation of the stipulated conservation area is >75% of its total boundary **<u>Fair</u>**: Delineation of the stipulated conservation area is 50–75% of its total boundary **<u>Bad</u>**: Delineation of the stipulated conservation area is <50% of its total boundary
	E2.2.2 Delineation of the stipulated animal corridor	**<u>Excellent</u>**: Delineation of the stipulated animal corridor is >75% of its total boundary **<u>Fair</u>**: Delineation of the stipulated animal corridor is 50–75% of its total boundary **<u>Bad</u>**: Delineation of the stipulated animal corridor is <50% of its total boundary
	E2.2.3 Realization and quality of boundaries	**<u>Excellent</u>**: Realization of boundary delineation is equal to the total protected area **<u>Fair</u>**: Realization of boundary delineation is >50% of the total protected area **<u>Bad</u>**: Realization of boundary delineation is <50% of the total protected area

Appendix C (continued)

Indicator	Selected verifier	Possible definition of verifier*)
E2.3 Damage intensity to endangered/ endemic/protected species in the special areas	E2.3.1 Frequency and type of damage towards endangered wild animal species	**Excellent**: There is no disturbance towards endangered animal species **Fair**: There are low disturbances towards endangered animal species and the controlling efforts are adequate **Bad**: There are high disturbances towards endangered animal species and the controlling efforts are inadequate
	E2.3.2 Frequency and type of damage towards endangered plant species	**Excellent**: There is no disturbance towards endangered plant species **Fair**: There are low disturbances towards endangered plant species and the controlling efforts are adequate **Bad**: There are high disturbances towards endangered plant species and the controlling efforts are inadequate
E2.4 Condition of endangered/ende mic/protected species in the special areas	E2.4.1 Abundance of endangered plant and wild animal species in special area	**Excellent**: Abundance of endangered plant and animal species in special area is >80% of those in virgin forest **Fair**: Abundance of endangered plant and animal species in special area is 60–80% of those in virgin forest **Bad**: Abundance of endangered plant and animal species in special area is <60% of those in virgin forest
	E2.4.2 Abundance of endangered plant and wild animal species in logged-over area	**Excellent**: Abundance of endangered plant and animal species in logged-over area is >80% of those in virgin forest **Fair**: Abundance of endangered plant and animal species in logged-over area is 60–80% of those in virgin forest **Bad**: Abundance of endangered plant and animal species in logged-over area is <60% of those in virgin forest
	E2.4.3 Abundance of endangered plant and wild animal species in virgin forest	**Excellent**: Abundance of endangered plant and animal species in virgin forest is >80% of those in the existing standard **Fair**: Abundance of endangered plant and animal species in virgin forest is 60–80% of those in the existing standard **Bad**: Abundance of endangered plant and animal species in virgin forest is <60% of those in the existing standard
E2.5 Impact intensity of production management activities towards endangered/ende mic/protected plant species and their habitat	E2.5.1 Level of similarities between logged-over area and virgin forest	**Excellent**: Index of similarity between logged-over area and virgin forest is >50% **Fair**: Index of similarity between logged-over area and virgin forest is 25–50% **Bad**: Index of similarity between logged-over area and virgin forest is <25%

Appendix C (continued)

Indicator	Selected verifier	Possible definition of verifier*)
E2.5	E2.5.2 Number of endangered plant species in logged-over area	**Excellent**: Number of endangered plant species (seedlings, saplings, poles, trees) in logged-over area is more than or equal to those in virgin forest **Fair**: Number of endangered plant species (seedlings, saplings, poles, trees) in logged-over area is >80% of those in virgin forest **Bad**: Number of endangered plant species (seedlings, saplings, poles, trees) in logged-over area is <80% of those in virgin forest
	E2.5.3 Number of endangered plant species in virgin forest	**Excellent**: Number of endangered plant species (seedlings, saplings, poles, trees) in virgin forest is >75% of those in the existing standard **Fair**: Number of endangered plant species (seedlings, saplings, poles, trees) in virgin forest is 50–75% of those in the existing standard **Bad**: Number of endangered plant species (seedlings, saplings, poles, trees) in virgin forest is >50% of those in the existing standard
E2.6 Impact intensity of production management activities towards endangered/endemic/protected wild animal species and their habitat	E2.6.1 Habitat condition of endangered wild animal species in virgin forest and logged-over area	**Excellent**: Degree of habitat fragmentation in logged-over area is <15% **Fair**: Degree of habitat fragmentation in logged-over area is 15–25% **Bad**: Degree of habitat fragmentation in logged-over area is >25%
	E2.6.2 Number of endangered wild animal species in virgin forest and logged-over area	**Excellent**: Number of endangered wild animal in logged-over area is more than or equal to those in virgin forest **Fair**: Number of endangered wild animal in logged-over area is >80% of those in virgin forest **Bad**: Number of endangered wild animal in logged-over area is <80% of those in virgin forest
E2.7 Security of endangered/ endemic/protected plant species and their habitat	E2.7.1 Condition of endangered plant species in logged-over area	**Excellent**: The number and condition of plant species are increase **Fair**: The number and condition of plant species are fairly increase **Bad**: The number and condition of plant species are decrease
	E2.7.2 SOP for plant security	**Excellent**: SOP for plant security is adequate **Fair**: SOP for plant security is fairly adequate **Bad**: SOP for plant security is inadequate
E2.8 Security of endangered/ endemic/protected wild animal species and their habitat	E2.8.1 Condition of endangered wild animal species in logged-over area	**Excellent**: The number and condition of plant species are increase **Fair**: The number and condition of plant species are fairly increase **Bad**: The number and condition of plant species are decrease
	E2.8.2 SOP for animal security	**Excellent**: SOP for animal security is adequate **Fair**: SOP for animal security is fairly adequate **Bad**: SOP for animal security is inadequate

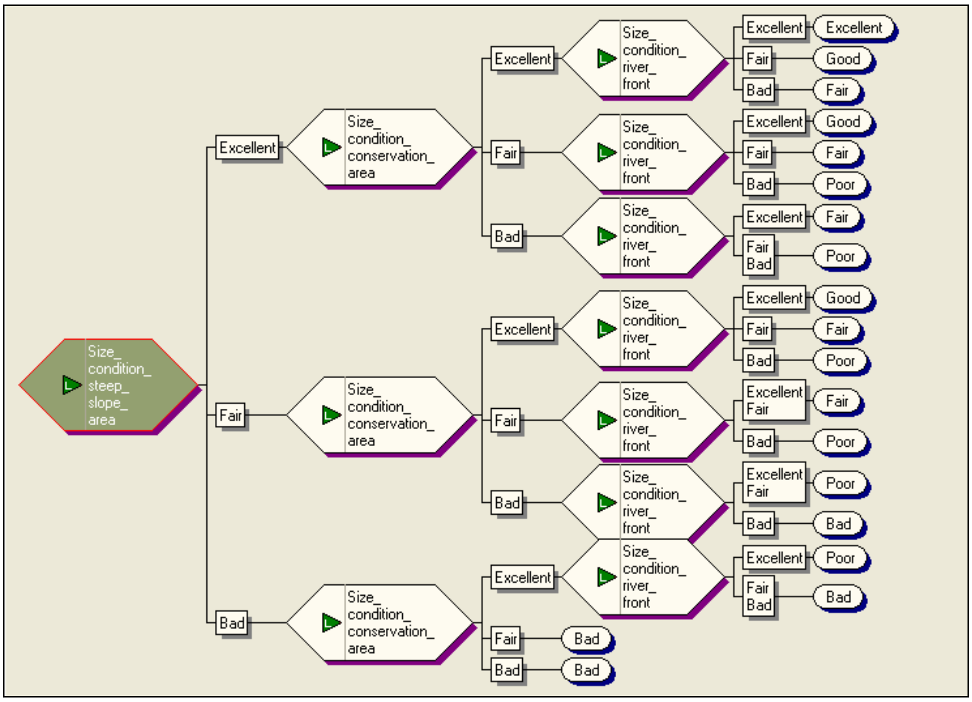
**) For the purpose of this study only, need further investigations*

Appendix D. The rule base used in the FRB-2 model for aggregating verifiers of the ecological indicators of SFM in the LEI system

D.1. The rules used for aggregating verifiers under the stability of ecosystem criteria

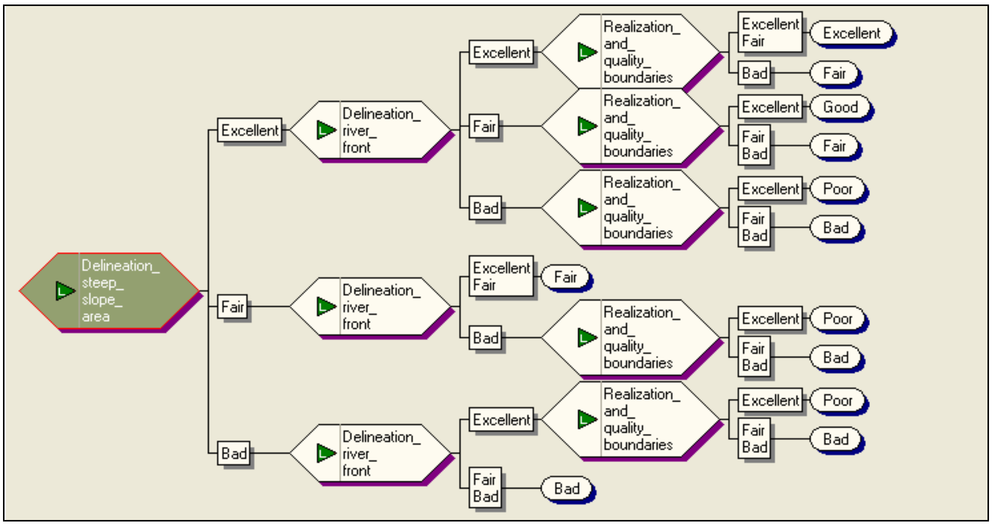
Indicator E1.1: Proportion of a well-functioning protected area to the total area that should be protected and has already been stipulated and/or acknowledged by relevant parties

To maintain stability of forest ecosystem in a forest management unit, proportion of a well-functioning protected area has to be established properly. Performance of this indicator can be assessed by various verifiers. However, for the current study area, the experts considered that three verifiers, i.e. size and condition of steep slope (>40%) area, and size and condition of biodiversity conservation area, size and condition of river front, are relevant verifiers to assess this indicator. These verifiers are complement to each other and have almost equal contributions to the performance of this indicator; hence the rules are as follows:



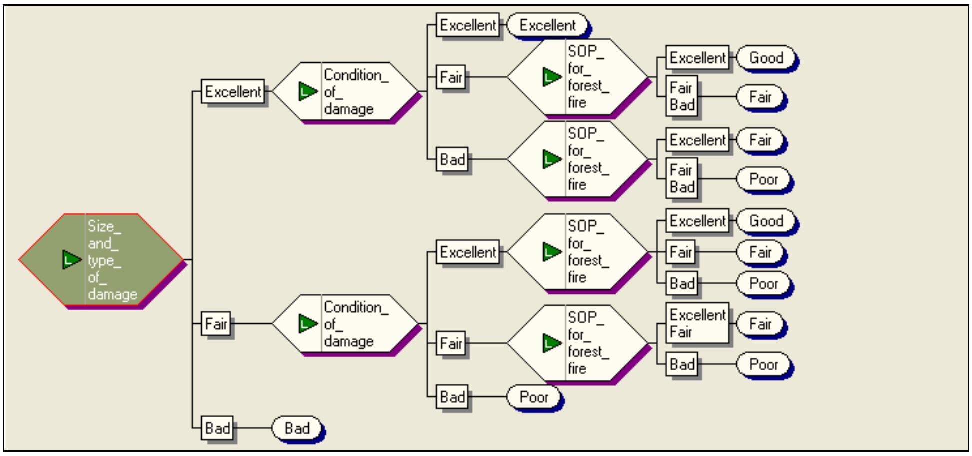
Indicator E1.2: Proportion of a well-managed protected area to the total size that should be protected and already delineated in the field

Boundaries delineation of the forest management unit as well as the protected area is required in order to maintain the stability of forest ecosystem. To assess performance of indicator E1.2, the experts considered that the most important verifier is delineation of a well-managed steep slope area, the second important is delineation of a well-managed river front, and the last important is realization and quality of the boundaries. Performance of E1.2 highly depends on the first and second important verifiers. If they are good, then performance of E1.2 will be good or excellent. The rules to assess this indicator are as follows:



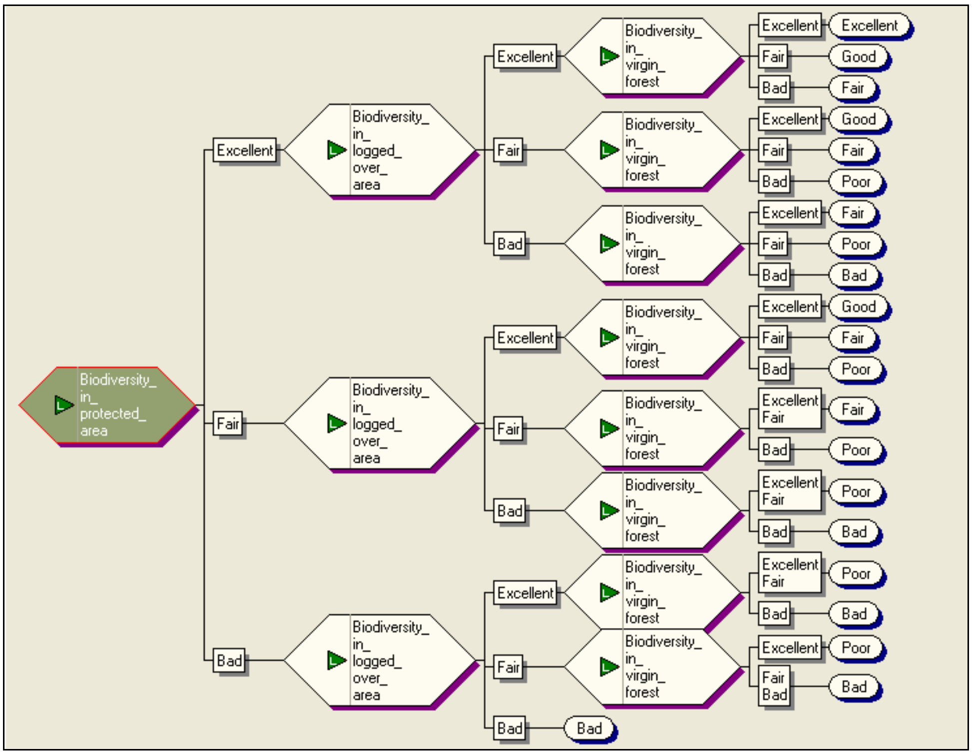
Indicator E1.3: Intensity of damage in the protected areas, including fire hazards

In a forest management unit, damages in the protected area are usually caused by human activities and forest fires. The expert considered that size and type of damaged protected area is most important verifier to assess this indicator. The second important verifier is condition of damaged protected area, and the third important is SOP (Standard Operating Procedure) for forest fire prevention. In this case, if performance of the size and type of damaged protected area is bad then performance of indicator E1.3 will be bad as well. Based on the expert judgments as well as description of intensity scale of indicator E1.3 (see LEI, 2000), the rules to assess this indicator are as follows:



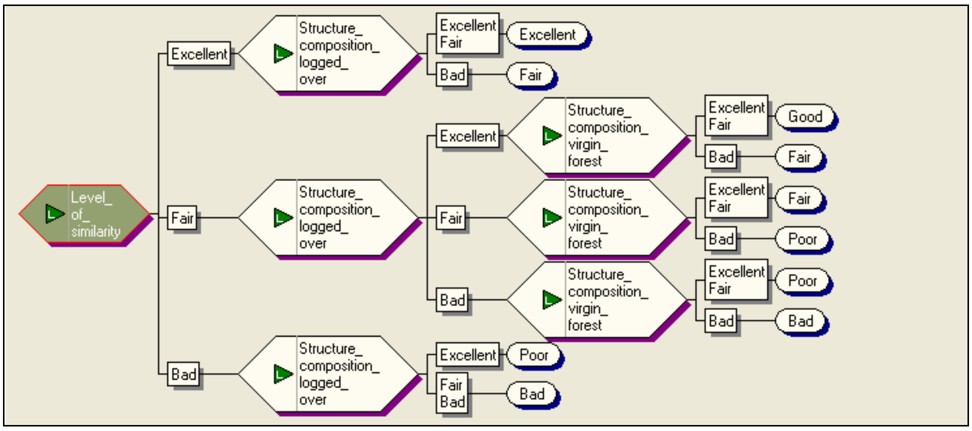
Indicator E1.4: Condition of flora and/or fauna species diversity in protected area in various forest formations/types within management units

Condition of flora and fauna in protected area can be assessed by comparing its species diversity to the condition of virgin forest and logged-over area. Therefore, the verifiers of this indicator have equal order of importance. Indeed, all the verifiers are interrelated and required to verify performance of this indicator. It means that performance of indicator E1.4 depends on performance of all the verifiers. Therefore, the rules to assess this indicator are as follows:



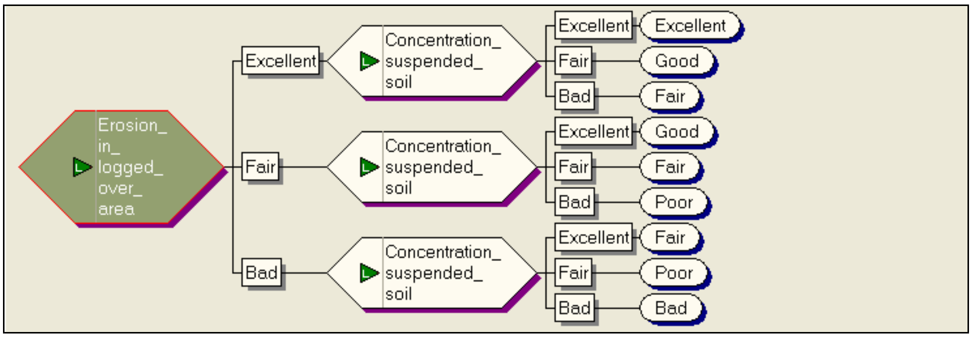
Indicator E1.5: Damage intensity of forest structure and plant species composition

Damage intensity of forest structure and plant species composition in protected area has negative effects to stability of forest ecosystem. This indicator can be verified by examining the structure and composition of plant species in virgin forest and logged-over area and level of similarity between logged-over area and virgin forest. In this case, the most important verifier is level of similarity between logged-over area and virgin forest. The indicator will have an excellent performance only if the index of similarity more than 50%. The second important verifier is structure and composition of plant species in logged-over area, whereas the third important verifier is structure and composition of plant species in virgin forest area. Performance of indicator E1.5 depends highly on the first and the second verifiers. Based on the description of intensity scale of indicator E2.5 (see LEI, 2000), the rules to assess this indicator would be as follows:



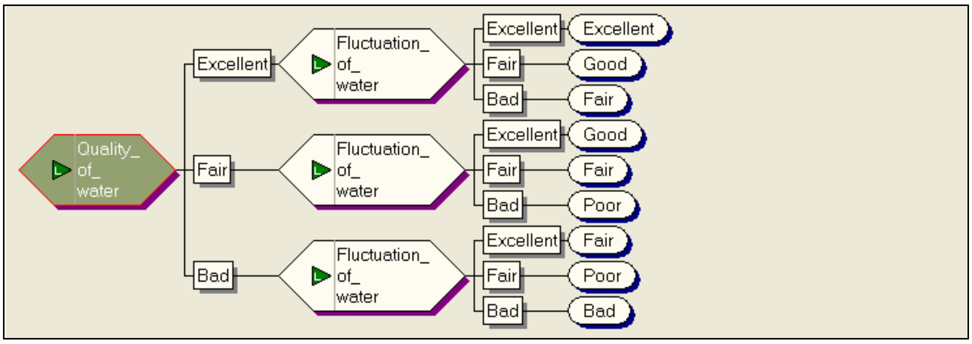
Indicator E1.6: Impact intensity of production management activities on soil

High intensity of production management activities on soil revealed that a forest management unit has not considered environmental aspects, whereas it leads to give negative effects to the stability of forest ecosystem. This indicator can be assessed by two verifiers, i.e. erosion level in logged-over area (as most important verifier) and concentration of suspended soil (as less important verifier). If there is high erosion in logged-over area, then the impact intensity of production management activities on soil will high as well. In addition, high concentration of suspended soil also indicates the high impact of production management activities. Therefore, performance of this indicator depends on performance of both verifiers. In this case, both verifiers imply risk in which a good performance is those that give a lower impact. Based on description of the intensity scale of indicator E1.6 (see LEI, 2000), the complete rules for assessing this indicator are as follows:



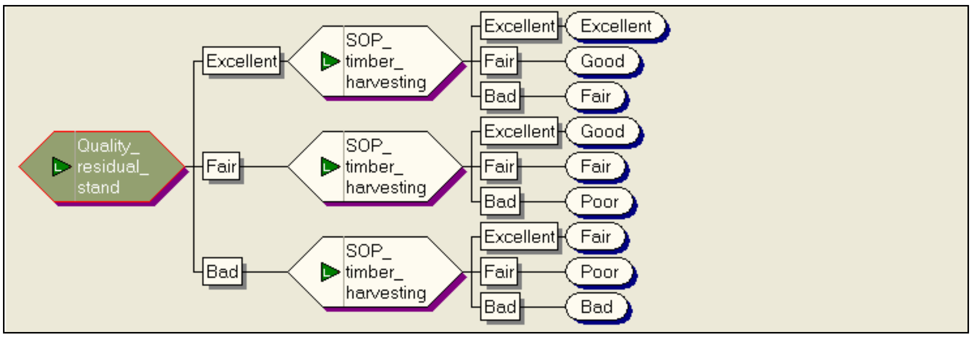
Indicator E1.7: Impact intensity of production management activities in water

Similar to the indicator E1.6, high intensity of production activities in water will give negative effects to the stability of forest ecosystem. The impacts can be assessed by examining quality of river or other water bodies and fluctuation of rivers and other water bodies. In this case, water quality (of river and other water bodies) is the first important verifier to assess intensity of the impact, whereas the fluctuation of rivers and other water bodies is second important verifier. However, as stated in the description of intensity scale of indicator E1.7 (see LEI, 2000), performance of this indicator depends on the performance of both verifiers as expressed in the following rules:



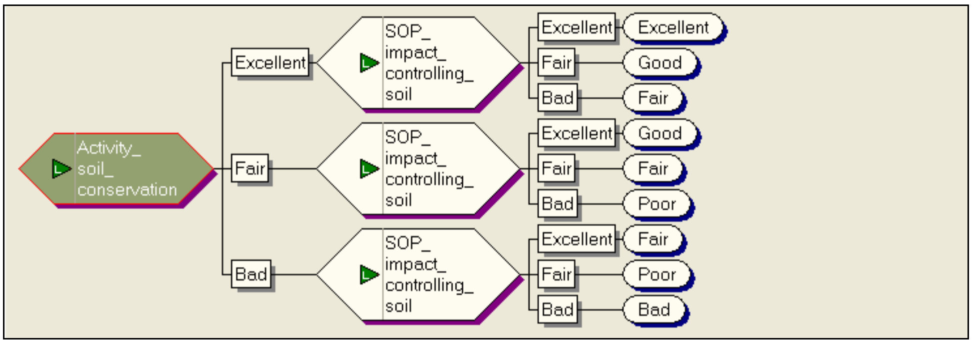
Indicator E1.8: Effectiveness of damage management of forest structure and composition

Performance of the forest management unit in managing the damage of forest structure and composition can be assessed by using two verifiers, i.e. SOP (standard operating procedure) for timber harvesting and quality of residual stand species. Here, the quality of residual stand species is considered as most important verifier and another verifier is least important. Condition and quality of residual stand can indicate the effectiveness of damage management due to timber harvesting. In addition, availability of SOP for timber harvesting will ensure that the forest management unit has serious efforts to minimize damages of forest structure. Based on description of intensity scale of indicator E1.8 as presented in LEI (2000), the complete rules to assess this indicator are as follows:



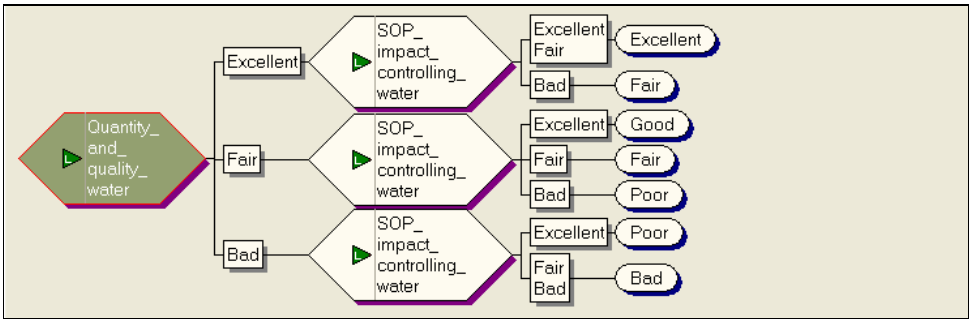
Indicator E1.9: Effectiveness of controlling techniques on the impact of production management activities on soil

Effectiveness of impact controlling on soil indicates seriousness of the forest management unit to support the stability of forest ecosystem. This indicator can be assessed by using two verifiers, i.e. SOP for impact controlling on soil and activity of soil conservation in logged-over area. In this case, the activity of soil conservation in logged-over area is considered as most important verifier, because it implies the real activities of forest management unit to minimize the impacts. The availability of SOP for impact controlling on soil is considered as second important verifier. Similar to the indicator E1.8, performance of indicator E1.9 would also highly depend on the performance of both verifiers. From the description of intensity scale of indicator E1.9 (see LEI, 2000), the appropriate rules to assess this indicator are as follows:



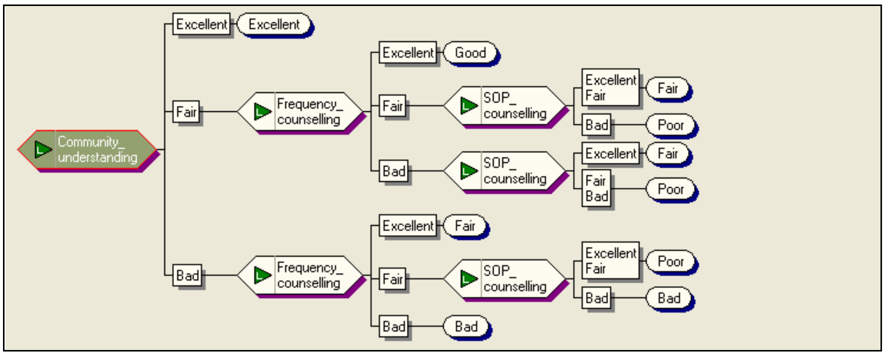
Indicator E1.10: Effectiveness of controlling techniques on the impact of production management activities on water

Similar to the indicator E1.9, this indicator also assesses efforts of the forest management unit to minimize impacts of production management on water. Here, the most important verifier is quantity and quality of water and the second important is SOP (standard operating procedure) for impact controlling on water. The first verifier implies a real condition of water that affected by production management activities, whereas the second one implies a series of procedure and activity that has to be carried out to minimize the impacts. Hence, performance of indicator E1.10 depends highly on performance of the first verifier. However, bad performance of the second verifier would decrease performance of this indicator. Based on the description of intensity scale of indicator E1.10 (see LEI, 2000), the rules to assess this indicator are as follows:



Indicator E1.11: Effectiveness of counseling on the importance of forest ecosystem conservation as a life support system, the impact of abundant harvest activities to forest ecosystem, and the importance of endangered/endemic/protected species conservation

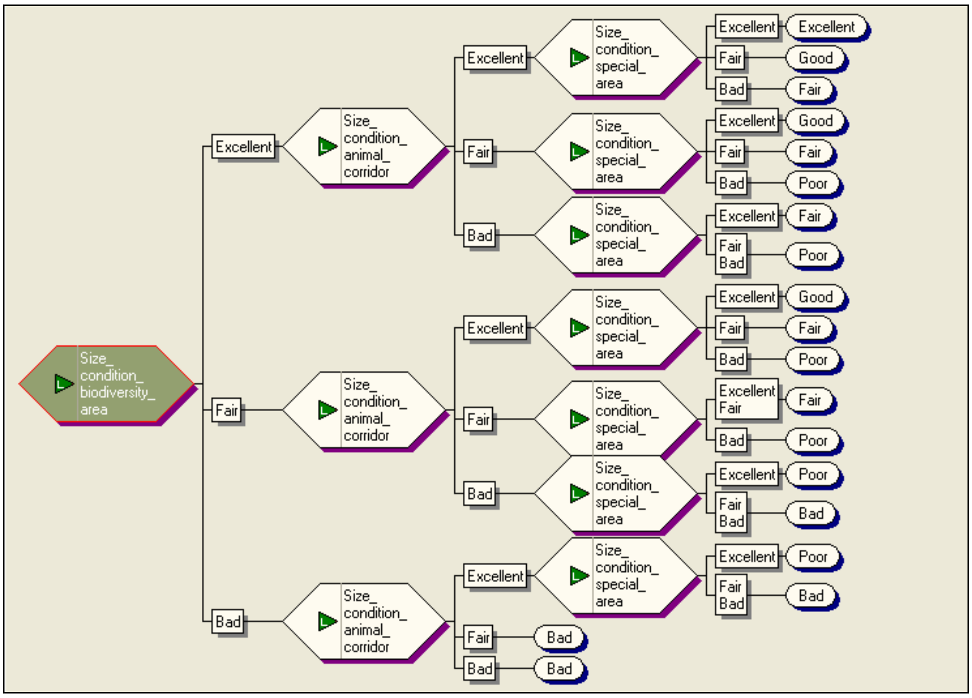
Counseling on forest conservation plays important role to increase awareness of community on the importance of forest ecosystem. Therefore, community understanding of forest conservation is a main goal in counseling program and hence it becomes the most important verifier to assess the effectiveness of such counseling. The second important verifier is frequency of counseling in which high frequency will ensure better understanding of community. The third important verifier is SOP for counseling in which it provides guidelines to perform the counseling. Performance of indicator E1.11 highly depends on performance of the first verifier. However, performance of the second and the third verifier will also have a significant effect to increase or decrease performance of this indicator. The rules to assess this indicator are as follows:



D.2. The rules used for aggregating verifiers under the stability of ecosystem criteria

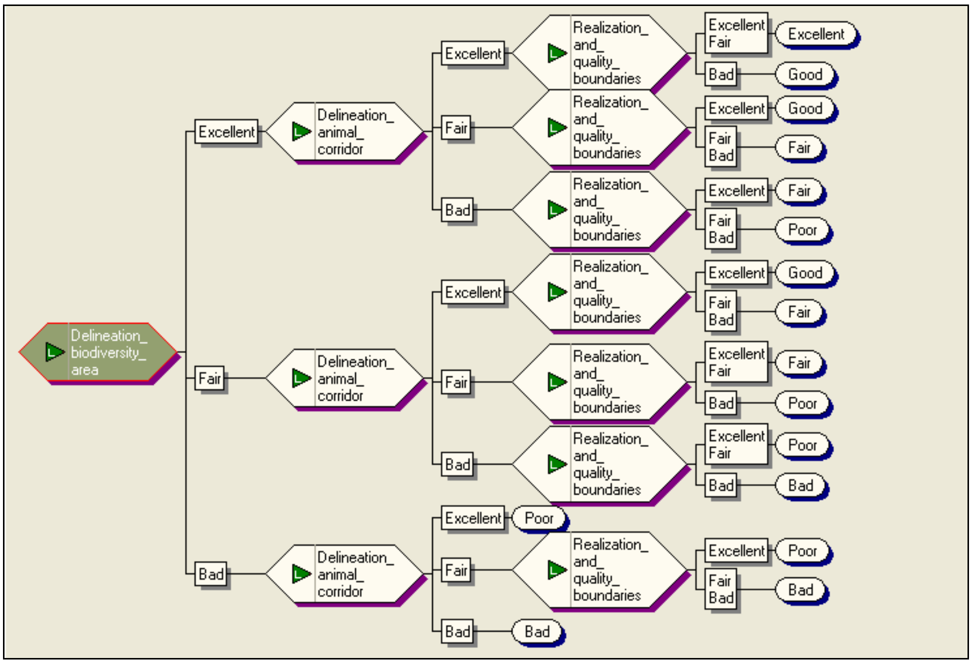
Indicator E2.1: Proportion of protected area that has been stipulated based on consideration of the existence of endangered/endemic/protected species or unique ecosystem (special area) and/or has been recognized by relevant parties

Availability of protected area for endangered species that has been stipulated by relevant parties indicates a great contribution of a forest management unit towards survival of endangered species in the concession. The relevant verifiers to assess this indicator are size and condition of stipulated biodiversity conservation area (as most important verifier), size and condition of stipulated animal corridor (as second important verifier), and size and condition of stipulated other special area (as last important verifier). Since these verifiers complement each other, hence performance of the indicator depends on the performance of all the verifiers as presented in the following rules:



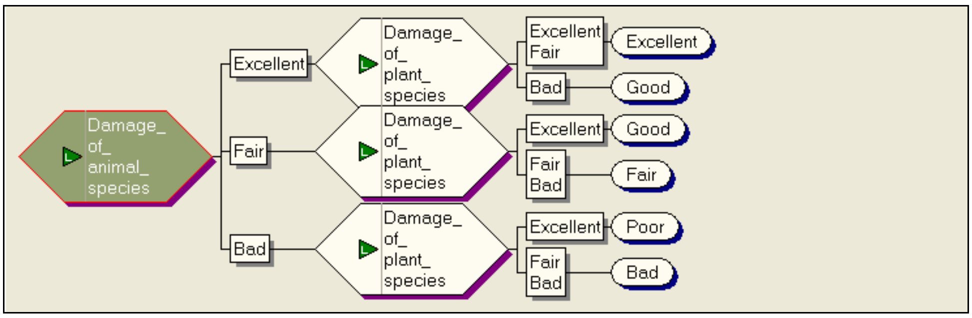
Indicator E2.2: Proportion of well-designed protected area, specifically designed for the survival of endangered/endemic/protected species or protected unique ecosystem that has been delineated in the field

Delineation of special area is required to support survival of endangered species in a forest management unit. Assessment of this indicator is focused to check the realization of such delineation. In this case, the most important verifier to assess this indicator is delineation of the stipulated biodiversity conservation area. The second important verifier is delineation of the stipulated animal corridor. The last important verifier is realization and quality of boundaries. However, performance of all the verifiers should be considered to judge performance of indicator E2.2. Therefore, the rules to assess this indicator are as follows:



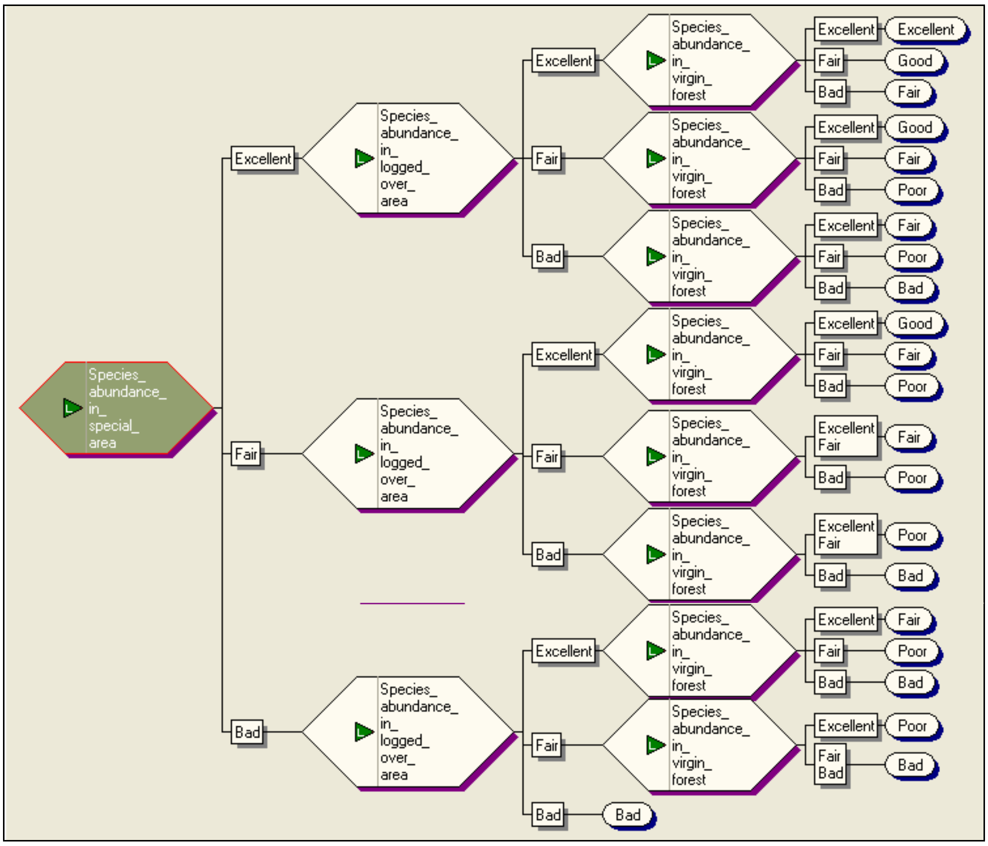
Indicator E2.3: Damage intensity to endangered/endemic/protected species in the special areas

Damage intensity in the special areas is a useful indicator to determine whether or not the special area is well-functioning to maintain survival of endangered species. This indicator can be assessed using two verifiers, i.e. frequency and type of damage towards endangered wild animal species (as most important verifier) and frequency and type of damage towards endangered plant species (as last important verifier). It is important to note here that assessing damage towards endangered animal species is easier than towards plant species which is usually very rare in a concession area. Since these verifiers imply risk, then minimum or no damage is preferred so that an excellent performance of these verifiers implies little or no damage towards either plant or animal species. The rules to assess this indicator are as follows:



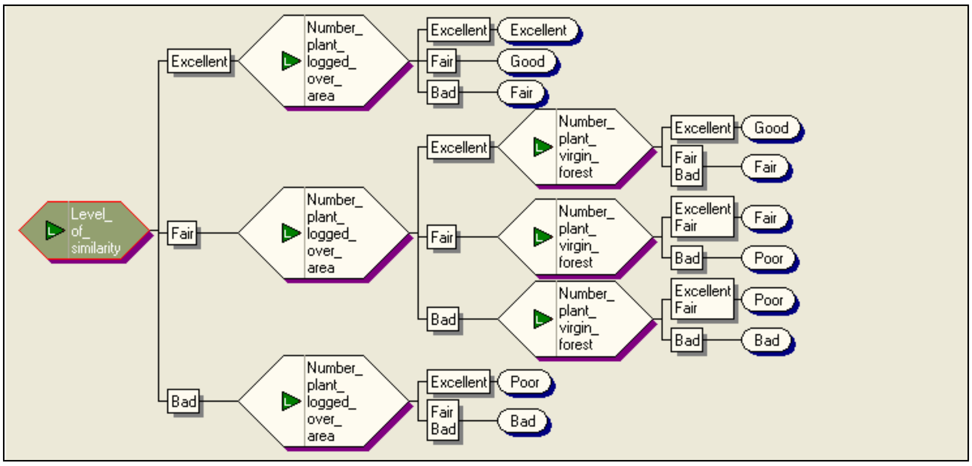
Indicator E2.4: Condition of endangered/endemic/protected species in the special areas

Abundance of endangered species is an appropriate parameter to assess whether or not the special area supports to maintain survival of endangered species. In this context, abundance of endangered plant and wild animal species in special area, virgin forest, and logged-over area are considered as relevant verifiers to assess indicator E2.4. These verifiers are interrelated to each other so that they have equal order of importance. Therefore, performance of all the verifiers should be considered in assessing performance of this indicator as presented in the following rules:



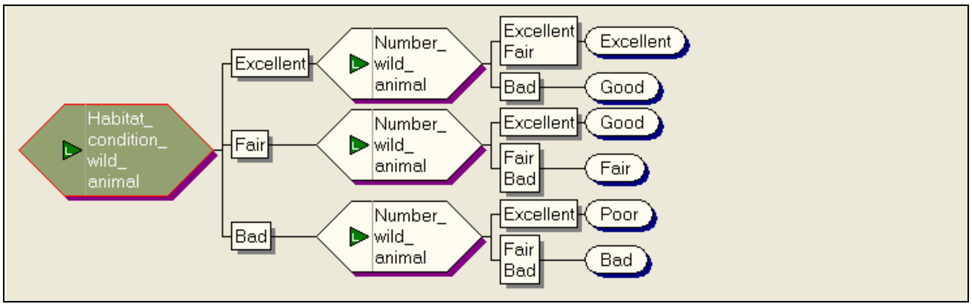
Indicator E2.5: Impact intensity of production management activities towards endangered/endemic/ protected plant species and their habitat

Impact intensity to endangered plant species is a useful indicator to measure whether production management activities support to maintain biodiversity in the concession area. This indicator can be assessed by using three verifiers, i.e. level of similarities between logged-over area and virgin forest (as most important verifier), number of endangered plant species in logged-over area (as second important verifier), and number of endangered plant species in virgin forest (as last important verifier). Based on the description of intensity scale of indicator E2.5 (see LEI, 2000), the rules to assess this indicator would be as follows:



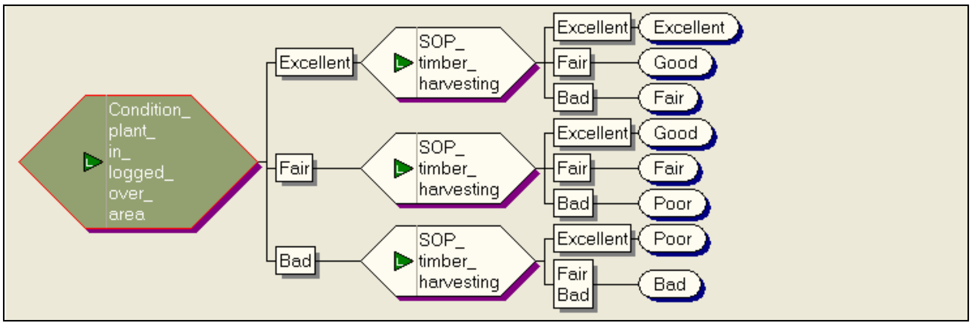
Indicator E2.6: Impact intensity of production management activities towards endangered/endemic/ protected wild animal species and their habitat

Similar to the indicator E2.5, impact intensity to endangered wild animal species is a useful indicator to assess survival of endangered species in a concession area. This indicator can be assessed by examining the habitat condition of endangered wild animal in virgin forest and logged-over area and by counting the number of endangered wild animal in such areas. In this case, the habitat condition is most important verifier because it would be easier to be checked in the field even an assessor could not find and count the animals directly. The rules to assess this indicator are as follows:



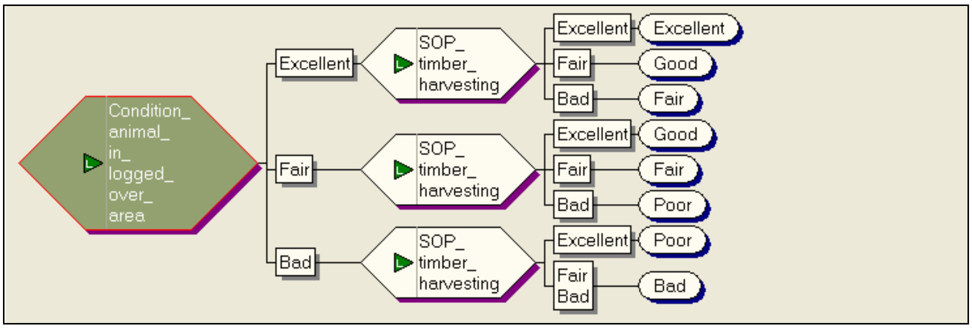
Indicator E2.7: Security of endangered/endemic/protected plant species and their habitat

Security of endangered plant species in a production forest is absolutely required in order to minimize impact of timber harvesting and to ensure the survival of endangered plant species. Therefore, condition of endangered plant species in logged-over area is the most important verifier to assess this indicator. In addition, SOP for timber harvesting can be used as an additional verifier. Performance of indicator E2.7 depends highly on performance of the first verifier which implies the real condition of endangered species in the concession area. Based on the description of intensity scale of indicator E2.7 (see LEI, 2000), the rules to assess this indicator are as follows:



Indicator E2.8: Security of endangered/endemic/protected wild animal species and their habitat

Security of endangered wild animal species in a production forest can be achieved only if there is no serious damage of animal habitat due to timber harvesting activities. In this case, the most important verifier is condition of endangered wild animal in logged-over area because it can reflect level of disturbance to the animal habitat. Another verifier is SOP for timber harvesting, particularly some relevant procedures that support to the survival of endangered animal species. These verifiers complement each other, hence their performances should be considered in assessing indicator E2.8. Based on the description of intensity scale of indicator E2.8 (see LEI, 2000), the rules to assess this indicator are as follows:



Appendix E. The pairwise comparison matrices used to derive the normalized crisp values for each ecological indicator

Indicator E1.1

E1.1	E	G	F	P	B
E	1	**2**	**4**	**7**	**9**
G	0.500	1	**2**	**5**	**7**
F	0.250	0.500	1	**3**	**5**
P	0.143	0.200	0.333	1	**2**
B	0.111	0.143	0.200	0.500	1

Indicator E1.2

E1.2	E	G	F	P	B
E	1	**2**	**4**	**6**	**8**
G	0.500	1	**2**	**4**	**6**
F	0.250	0.500	1	**2**	**4**
P	0.167	0.250	0.500	1	**2**
B	0.125	0.167	0.250	0.500	1

Indicator E1.3

E1.3	E	G	F	P	B
E	1	**3**	**5**	**7**	**9**
G	0.333	1	**2**	**4**	**6**
F	0.200	0.500	1	**2**	**4**
P	0.143	0.250	0.500	1	**2**
B	0.111	0.167	0.250	0.500	1

Indicator E1.4

E1.4	E	G	F	P	B
E	1	**1**	**3**	**5**	**7**
G	1.000	1	**1**	**3**	**5**
F	0.333	1.000	1	**1**	**3**
P	0.200	0.333	1.000	1	**2**
B	0.143	0.200	0.333	0.500	1

Indicator E1.5

E1.5	E	G	F	P	B
E	1	**2**	**4**	**6**	**9**
G	0.500	1	**2**	**4**	**7**
F	0.250	0.500	1	**2**	**5**
P	0.167	0.250	0.500	1	**2**
B	0.111	0.143	0.200	0.500	1

Indicator E1.6

E1.6	E	G	F	P	B
E	1	**2**	**4**	**6**	**9**
G	0.500	1	**2**	**4**	**7**
F	0.250	0.500	1	**2**	**5**
P	0.167	0.250	0.500	1	**3**
B	0.111	0.143	0.200	0.333	1

Indicator E1.7

E1.7	E	G	F	P	B
E	1	**2**	**4**	**6**	**8**
G	0.500	1	**2**	**4**	**6**
F	0.250	0.500	1	**2**	**4**
P	0.167	0.250	0.500	1	**2**
B	0.125	0.167	0.250	0.500	1

Indicator E1.8

E1.8	E	G	F	P	B
E	1	**2**	**5**	**7**	**9**
G	0.500	1	**3**	**5**	**7**
F	0.200	0.333	1	**2**	**4**
P	0.143	0.200	0.500	1	**2**
B	0.111	0.143	0.250	0.500	1

Indicator E1.9

E1.9	E	G	F	P	B
E	1	**2**	**5**	**7**	**9**
G	0.500	1	**3**	**5**	**7**
F	0.200	0.333	1	**2**	**4**
P	0.143	0.200	0.500	1	**2**
B	0.111	0.143	0.250	0.500	1

Indicator E1.10

E1.10	E	G	F	P	B
E	1	**2**	**5**	**7**	**9**
G	0.500	1	**3**	**5**	**7**
F	0.200	0.333	1	**2**	**4**
P	0.143	0.200	0.500	1	**2**
B	0.111	0.143	0.250	0.500	1

Appendix E (continued)

Indicator E1.11

E1.11	E	G	F	P	B
E	1	**2**	**5**	**7**	**9**
G	0.500	1	**3**	**5**	**7**
F	0.200	0.333	1	**2**	**4**
P	0.143	0.200	0.500	1	**2**
B	0.111	0.143	0.250	0.500	1

Indicator E2.1

E2.1	E	G	F	P	B
E	1	**2**	**4**	**7**	**9**
G	0.500	1	**2**	**5**	**7**
F	0.250	0.500	1	**3**	**5**
P	0.143	0.200	0.333	1	**2**
B	0.111	0.143	0.200	0.500	1

Indicator E2.2

E2.2	E	G	F	P	B
E	1	**2**	**4**	**6**	**8**
G	0.500	1	**2**	**4**	**6**
F	0.250	0.500	1	**2**	**4**
P	0.167	0.250	0.500	1	**2**
B	0.125	0.167	0.250	0.500	1

Indicator E2.3

E2.3	E	G	F	P	B
E	1	1	**3**	**5**	**7**
G	1.000	1	**2**	**4**	**6**
F	0.333	0.500	1	**2**	**4**
P	0.200	0.250	0.500	1	**2**
B	0.143	0.167	0.250	0.500	1

Indicator E2.4

E2.4	E	G	F	P	B
E	1	**1**	**3**	**5**	**7**
G	1.000	1	**1**	**3**	**5**
F	0.333	1.000	1	**1**	**3**
P	0.200	0.333	1.000	1	**2**
B	0.143	0.200	0.333	0.500	1

Indicator E2.5

E2.5	E	G	F	P	B
E	1	**2**	**4**	**6**	**9**
G	0.500	1	**2**	**4**	**7**
F	0.250	0.500	1	**2**	**5**
P	0.167	0.250	0.500	1	**2**
B	0.111	0.143	0.200	0.500	1

Indicator E2.6

E2.6	E	G	F	P	B
E	1	**3**	**5**	**7**	**9**
G	0.333	1	**2**	**4**	**6**
F	0.200	0.500	1	**2**	**4**
P	0.143	0.250	0.500	1	**2**
B	0.111	0.167	0.250	0.500	1

Indicator E2.7

E2.7	E	G	F	P	B
E	1	**2**	**5**	**7**	**9**
G	0.500	1	**3**	**5**	**7**
F	0.200	0.333	1	**2**	**4**
P	0.143	0.200	0.500	1	**2**
B	0.111	0.143	0.250	0.500	1

Indicator E2.8

E2.8	E	G	F	P	B
E	1	**2**	**5**	**7**	**9**
G	0.500	1	**3**	**5**	**7**
F	0.200	0.333	1	**2**	**4**
P	0.143	0.200	0.500	1	**2**
B	0.111	0.143	0.250	0.500	1

Where:
E = excellent
G = good
F = fair
P = poor
B = bad