UNIVERSITY OF BIRMINGHAM

PhD in Civil Engineering

A METHODOLOGY TO ASSSESS THE VULNERABILITY OF RURAL COMMUNITIES TO LACK OF ACCESS

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ABSTRACT

Many rural communities in developing countries are vulnerable to the disruption of access. The roads and transport services they rely on to access goods and services are often disrupted by climate-induced events (i.e. geohazards). There has been an increase in such disruptions due to changes in climate and land use, yet the budget available in many developing countries to improve community access remains scarce. Accordingly, there is a need for increased funding to improve rural access and to prioritise investment. This requires an understanding of the socio-economic benefits of investment in rural infrastructure and an equitable means by which the needs of communities can be compared so that limited budget can be spent on communities in greatest need of investment.

To address the above issue, this doctoral research developed a vulnerability-based assessment methodology and model that considers the likelihood and impacts of access disruption to a community and the capacity of the community to cope with and adapt to impacts and to improve its resilience to future events. The methodology and model incorporate fuzzy approaches (e.g. uniform formatting number, fuzzy analytical hierarchy process and fuzzy system) to address data uncertainty.

The use of the methodology/model is illustrated using data obtained from four villages in China. The results from the case study illustrate that the developed approach is robust, that is can take into account data uncertainties and that it is capable of providing a means by which the access needs of different communities can be prioritised equitably and transparently.

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GLOSSARY OF TERMS

Aggregation uncertainty Uncertainty in composing vulnerability components

AHP Analytical hierarchical procedure; an approach to address a complex problem by disaggregating it into several understandable problems

Aleatoric uncertainty Something that is unsure due to its irregular pattern

Asset A tangible and intangible resource that can be mobilised to address adverse impact

Biophysical vulnerability People, assets or places that are susceptible to external risk

CBA Cost benefit analysis; a method to analyse whether the benefits of an investment outweigh its costs

Compound proposition A combination of more than two simple propositions through logical connectives

Defuzzification A process to transform a fuzzy number (i.e. a multi-valued number) into an exact number

Epistemic uncertainty Something that is unsure due to imperfect knowledge about it

EV models Expanded vulnerability models; the modelling of biophysical and social vulnerabilities in a coupled human-and-environmental system

Exposure Biophysical vulnerability of roads serving a rural community to geohazards (e.g. flood)

Fuzzification A process to make an exact number fuzzy

Fuzzy AHP AHP developed by a fuzzy set where members are allowed to have partially membership

Fuzzy logic A kind of uncertainty logic that can address linguistic information-related uncertainty (e.g. approximately 2 meters) in a proposition

Fuzzy rule A compound proposition involving unclear linguistical information

Fuzzy rule base A collection of fuzzy rules

Fuzzy set A set that allows its members to have partial membership

Fuzzy system A system that reflects the relationship between the states of linguistic variables whose values are words or sentences rather than numbers

Hazardous event Risk event resulting from the loss of road access provision

IQL Information quality level; utilised to categorise data based on detail level

Judgment uncertainty Uncertainty in making judgment regarding numerical estimation

Linguistic terms Values of linguistic variables

Logic A pattern of reasoning by which conclusion is drawn from evidence

Logical connective Sentential connective (e.g. AND) that links two and more sentences

MCA Multi-criteria analysis; an approach to support a complex decision-making circumstance with several conflicting objectives that decision-makers value differently

Membership function A function that represents the membership of a member in a fuzzy set

PAR models Pressure and release model; combining biophysical and social vulnerabilities

Probabilistic logic A kind of uncertainty logic that uses probabilistic value to express the truth value of a proposition

Proposition A statement that expresses a judgment

R-H models Risk-hazard models; modelling of biophysical vulnerability

Resilience The capacity of a rural community to withstand impacts from exposure

Risk A chance of loss

Risk assessment An approach to understand risks and their causes, consequences and probabilities

Road asset The asset of physical road to be managed

Road asset management Co-ordinated activities to manage the physical road in a cost-effective manner for purpose of achieving an organisational goal

Sensitivity Social vulnerability of a rural community to disruptive road access provision

Simple proposition A single statement

Social vulnerability The susceptibility of a system (e.g. a community) due to its inability to cope with the impacts of external risk

SV models Social vulnerability models; modelling of social vulnerability

UFN Uniform formatting number

Uncertainty Unsureness regarding something

Uncertainty logic The logic for handling propositions whose truth value is neither completely true nor completely false

Vulnerability The degree to which a system is affected by something

Vulnerability assessment An approach to understand vulnerability and its causes

Vulnerability determinants Factors that determine vulnerability

CHAPTER 1 INTRODUCATION

1.1 Background

The provision of good (i.e. reliable, affordable and safe) rural access can reduce transport costs, fares and tariffs, increase the reliability of transport services, and increase transport volume and thereby contribute to socio-economic well-being and development (Hine et al., 2015). Such benefits typically rely on well-maintained all-season roads, and safe, reliable and affordable transport services. All season rural roads in good condition can reduce vehicle operation costs and travel times (Lokshin and Yemtsov, 2005; Danida, 2010), help to retain road connectivity during the wet season and facilitate the provision of transport services (Barwell, 1996; Anchirinah et al., 2008; Porter, 2013; Iimi et al., 2016; World Bank Group, 2016).

In particular, empirical studies have shown the provision of good rural roads in developing countries can (Njenga and Davis, 2003; Turner et al., 2004; Hine et al., 2015):

1. Facilitate domestic tasks (e.g. change in transport mode from head-loading to motorised transport, this is typically beneficial to women).
2. Facilitate agricultural and non-agricultural activities, including:
    a. Rise of farm gate prices determined by reduction in transport costs and enhancing the reliability of transport services.
    b. Increased volume of products and services sold due to increased traffic passing.
3. Increase income, expenditure, assets and livelihoods (e.g. reducing transport fares and tariffs could increase agricultural and non-agricultural activities, thereby, facilitate locally socio-economic development.

4. Improve the outcomes of education and health (e.g. higher enrolment, attendance and literacy rates; a larger number of health facilities, higher attendance at health facilities, higher life expectancy, lower child mortality and improvement of maternal health).
5. Reduce vulnerability (such as improved resilience due to increase in asset conditions and access to several necessary services).
6. Improve the quality and availability of government and Non-Government Organisation (NGO) (such external organisations can provide assistances for local rural communities; however, it is impossible for them to settle in locations that do not have reliable access).
7. Facilitate gender equality and empower women (e.g. reduction in female head-loading due to the availability of motorised transport).

However, approximately one billion people in developing countries still do not have access to all season roads severely constraining socio-economic development (World Bank, 2016; Hine et al., 2015). Lack of access to all season roads inevitably causes increased transport costs and travel times (World Bank Group, 2016). This in turn adversely impacts agricultural and non-agricultural activities, so as to negatively influence income, expenditure, and assets as mentioned above. For example, Guo et al. (2009) state that the high transport costs to market for famers living in east Africa due to poor local road condition has resulted in a lower level of farm gate prices for maize, decreasing farmers' income. A study by Willroth et al., (2011) found that people living in the villages of Ban Nam Khem and Khao Lak in Thailand, have low income levels, but high transport costs, and therefore the villagers typically do not have the savings or insurance to cope with the adverse effects of hazardous events, such as tsunamis.

1.2 Problem description

As mentioned above, rural roads serving communities in developing countries provide access to a range of goods, services and amenities (e.g. markets and healthcare centres) and thereby support rural social and economic development and poverty alleviation.

However, much of rural road infrastructure in developing countries is of poor quality and suffers from a lack of maintenance due to limited budgets (Hearn, 2014). In addition, most rural road networks in most developing countries consist predominantly of roads of earth and gravel construction and are accordingly readily damaged by climate-related hazardous events (i.e. geo-hazards such as landslides, flooding and erosion). Therefore, rural road access provision can be severely disrupted, particularly for communities which experience a wet season. In many regions the situation, it is likely to be made worse due to the effect of the changing climate and the resulting increased severe weather events. The resulting more frequent and severe geo-hazards have the potential to affect further rural road access provision (Hearn, 2014).

Although the road sectors in many developing countries are undergoing substantial reforms, these have mainly been focused on strategic road networks and expenditure on rural roads is often overlooked for a number of reasons. These reasons include political factors (e.g. preference for new construction over maintenance), insufficient road maintenance budgets, a lack of a maintenance culture, inadequate institutional arrangements, ineffective rural road asset management and a lack of a suitable means of arguing for funds for rural road maintenance where social benefits are significant (Burrow et al., 2016).

Consequently, there is a need to develop approaches which can be used by road authorities to argue for funds for rural road maintenance and upgrades and which can be used to prioritise limited budgets so that they are targeted to areas in greatest need. Although several road investment tools exist (such as HMD-4 (Highway Management and Development-4) (Kerali et al., 1998) or RED (Roads Economic Decision)) (Archondo-Callao, 2004), they tend to analyse road investment economically. For example, HDM-4, as a primary road investment tool, typically justifies an investment through analysing if the economic benefits of the investment exceed its costs, and such benefits only include reduction of vehicle operating costs and travel times. By contrast, RED’s focus is on rural road in particular for unpaved road. RED also consider saving in vehicle operation costs and travel times as investment benefits.

Accordingly, the existing road investment tools fails to as comprehensively as possible consider the socio-economic factors determining the degree to which an area is vulnerable to disruptive rural road access provision. Based on this, the development of an approach for rural road access vulnerability is the subject of this research.

1.3 Aim and objectives

The aim of this research is to develop an approach which can be used to assess the vulnerability of rural communities to disruptions in rural access caused by geo-hazards. The model is intended to assist road managers with the planning of appropriate road interventions by prioritising rural communities in most need of improved access, i.e. those communities which are most vulnerable to a lack of rural access provision.

To achieve this aim, this research has the following objectives (see Figure 4-1):

1. To explore methods of rural road investment prioritisation.

2. To explore vulnerability assessment approaches and their applicability for rural communities.
3. To explore approaches for dealing with uncertainty in data.
4. To demonstrate the applicability of the developed approach using a case study.

1.4 Benefits of the research

This research has developed for the first time a vulnerability-based assessment model through which road managers can prioritise rural road investments for rural communities. The model can be used to evaluate the degree to which a rural community is vulnerable to reduced access, and assists with:

- Identifying the determinants of rural community road access vulnerability.
- Quantitatively analysing the identified determinants of vulnerability.
- Taking into account uncertainties associated with the analysis of vulnerability.
- Evaluating the relative vulnerability of the communities considered.

1.5 Novelty of research

Novel feature(s) of this research is:

This research concerns the development of a methodology for vulnerability assessment for rural road investment prioritisation. It is believed that this is the first such approach. Within this methodology, Expanded Vulnerability (EV) models were utilised, this enables the consideration of vulnerability as comprehensively as possible. In addition, the methodology takes into account uncertainty in the fuzzy environment, i.e., fuzzy concept related approaches (such fuzzy AHP, fuzzy logic etc.) are used to deal with uncertainty.

1.6 Thesis organisation

This thesis is structured as following nine chapters:

Chapter 1 (this chapter) introduces the research subject in terms of the background, the problem description, and illustrates the aim and objectives of the research, along with the benefits and novelty of the research.

Chapter 2 summarises the findings from the literature of (a.) approaches for and (b.) uncertainty within road investment appraisal.

Chapter 3 summarises the findings from the literature of (a.) examples and models for and (b.) uncertainty within vulnerability assessment.

Chapter 4 develops a methodology consisting of (a.) the research methodology used to conduct this research, (b.) the theoretical framework for the development of a vulnerability assessment model, (c.) the consideration of uncertainty involved in the vulnerability model, and (d.) the approaches used for data collection.

Chapter 5 identifies the determinants of the rural community road access vulnerability model developed in the research. Thereafter, the identified vulnerability determinants are quantitatively analysed.

Chapter 6 presents the fuzzy logic approached developed to deal with uncertainty in the vulnerability assessment model described in chapter 4, i.e., utilisation of fuzzy numbers and a fuzzy system to respectively address (a.) uncertain judgement on parameter values and linguistic descriptors, and (b.) aggregation uncertainty.

Chapter 7 demonstrates the applicability of the vulnerability assessment model via a case study.

Chapter 8 presents a discussion of the research.

Chapter 9 draws the research conclusions and suggests recommendations for further research.

CHAPTER 2 ASSET MANAGEMENT

2.1 Introduction

As described in Chapter 1, road access provision in rural communities in developing countries is often disrupted and these communities are vulnerable to such disruption. Consequently, road assets serving these communities should be managed properly in order to provide reliable, affordable and safe access.

Through the relevant literature, although a number of organisations have defined asset management in general, two definitions are considered pertinent for this research. From the infrastructure (or performance) focused perspective, asset management is defined as a systematic process of maintaining, upgrading, and operating physical assets in a cost-effective manner (FHWA and AASHTO, 1996). Asset management in this context therefore seeks to provide a framework to deal with the short- and long-term planning horizons by not only integrating engineering principles into business practices and economic theory, but also offering tools to facilitate the more logical and organised methods of decision-making.

From the service focused angle, the Institute of Asset Management (IAM) (2002) defines asset management as the combination of management, financial, economic, engineering, and other practices for use with physical assets to provide the level of service required in a cost-effective manner. According to BS ISO 55000 (2014), the asset management includes advantages: (1.) improvement of financial performance, (2.) informed decision on asset investment, (3.) management of risk, (4.) illustration of social responsibility and compliance, (5.) enhanced reputation, (6.) improvement of organisational sustainability, and effectiveness and efficiency. For example, CIPFA (Charted Institute of Public Finance and Accountancy) estimates the 5% saving over the long term through managing the highway asset (2008).

2.2 Road asset management

According to Robinson (2008), road service derives from the provision of road assets. Hence, the aim of road asset management is to ensure that a road asset is performing properly so that the required level of service can be delivered cost effectively. Accordingly, this study uses a definition of asset management that refers in particular to road asset management (BSI, 2004), i.e., "*Systematic and co-ordinated activities and practices through which an organisation optimally manages its physical assets, and their associated performance, risk and expenditures over their life-cycle for the purposes of achieving its organisational strategic plan.*"

With respect to road asset management, it is considered to operate at three levels: strategic, programming, and operational (Robinson, 2008). At the strategic level, the decision-making about the management of road assets typically derives from the senior managers, it influences the entire organisation and the whole of the road network managed by an organisation in the long term. At the programming level, department/division heads or budget holders typically make tactical decisions for the medium-term affecting parts of the road network. At the operational level, the engineers, technicians, and operational staff are the major management decision makers. Operational level management activities normally affect units, sections and teams within the organisation, as well as impacting contractors and physical road sections.

The World Bank has introduced the concept of information quality levels (IQLs) to guide the data requirements at strategic, programming and operational levels (Paterson and Scullion, 1990). Four IQLs are defined. Typically, IQL-3 and IQL-4 refer to data with coarser level of detail and are required for programming and strategic planning (i.e., network level). IQL-1 and IQL-2 are related to data with the highest level of accuracy and recommended for project level analysis.

The intended output of this research is a vulnerability assessment model that is capable of evaluating rural community road access vulnerability and indicating the degree to which a rural community is more vulnerable to the disruption of access compared to other communities. Therefore, the model could be used to be a basis for the road investment prioritisation so as to assist allocating budget of road investments amongst considered communities where they are at risk of the disruptive access provision. This could make positive contribution to road asset management.

In the light of classification of road asset management and the data requirement at each managerial level above, the vulnerability model to be developed could help managing road asset at the programming level, thereby, the data requirement for the model is at IQL-3/IQL-4. As stated above, the outcomes of the application of the vulnerability model are numerical numbers indicating the degrees of different considered communities' vulnerabilities to the disruption of access. The premise postulated in this work is that the higher vulnerability a community has, the higher it's priority for road investment. Consequently, this model could help not only solving budget constraints, but also facilitating cost effectiveness of road investments.

2.2.1 Road investment appraisal approaches within road asset management

Through reviewing related literature on road asset management, road investment appraisal approaches, cost benefit analysis and multi criteria analysis, are identified to make a significant contribution to road asset management. Therefore, these approaches are elaborated below.

2.2.1.1 Cost benefit analysis

Cost Benefit Analysis (CBA) is an economic evaluation approach used by road agencies to appraise road investments (Bhandari et al., 2016). Its attempts to determine if the benefits of an investment outweigh its costs over a defined period of analysis – in other words, the economic viability of an investment.

Traditional CBA techniques have difficulty in taking into account unquantifiable benefits (e.g. community cohesion) and costs (e.g. noise) generated by road investment, as such benefits are complex to monetise (PIARC, 2013; Beria et al. 2012)). Therefore, a CBA's requirement for expressing all costs and benefits in monetary terms limits the evaluation of road investments to the economic dimension. In addition, CBA often requires large amounts of detailed and precise input data. This results in an expensive and time-consuming process of data collection. These issues may make the application of CBA to rural roads in developing countries problematic where sufficient and accurate data are difficult to obtain and the benefits of road investment are less easily quantified.

Despite these limitations of CBA, it is widely used in the road sector. Hence, the section below introduces two aspects of this analysis. Section 2.2.1.1.1 describes the criteria considered in road investment evaluation using CBA, while section 2.2.1.1.2 depicts several specific forms (or approaches) of CBA.

2.2.1.1.1 The components of CBA used for road investment appraisal

According to Couture et al. (2016), the costs of a road investment comprise capital costs and costs related to maintenance and rehabilitation, while the benefits are categorised into direct (or internal) benefits for road users and secondary benefits for non-road users. Normally, direct benefits consist of the savings of vehicle operating costs (VOC) and travel time, and safety improvements. VOC refers to the costs related to owning, operating, and maintaining a vehicle (Bennett and Greenwood, 2003b). VOCs are considered to be directly related to road pavement condition. The worse the condition the higher the VOCs, since poor road condition results in higher fuel and maintenance costs amongst other things (Bennett and Greenwood, 2003b).

A number of VOC models have been developed, such as the HDM 3 and HDM 4 VOC models (Bennett and Greenwood, 2003a, 2003b), as well as others deriving from the HDM 3 and HDM 4 (e.g. New Zealand NZVOC (Bennett, 1989), the Swedish VETO model (Hammarström and Karlsson, 1991), and the British COBA VOC module (United Kingdom Department of Transportation, 1993)).

With respect to travel time savings, an extensive body of literature has developed different values of time (VOT) (Börjesson et al., 2012; Habib and Weiss, 2014; Ojeda-Cabral et al., 2016; Rashedi et al., 2016), as VOT varies in light of diverse sorts of users and journeys (Gunn, 2001). To account for individual variation, it is standard practice to use an average VOT for work travel and a separate one for non-work travel (United Kingdom Department for Transport, 2014).

Regarding safety improvements, the resultant benefits can be treated as the avoided costs associated with dealing with accidents (such as the provision of emergency services) and/or a monetary value assigned to injuries and fatalities (Couture et al., 2016). Analogous to VOT, different countries assign diverse values to this. For instance, the highest value of an accident in US is 6.66 million dollars, while the lowest in Singapore is 0.1 million dollars, thereby, 66 times greater in the US than in Singapore (Gwee et al., 2011).

In addition to the aforementioned direct benefits, there are many secondary impacts related to road investments (such as a reduction in greenhouse gas emissions (GHG)). Typically, it is difficult to monetise these secondary impacts with CBA, but some attempts have been carried out. For example, Quinet (2004) monetises negative health effects caused by air pollution via the cost of medical services, and builds a relationship between particulates in the air and these effects. With respect to GHG, Metrolinx (2015) monetises the impacts of GHG via the local costs of GHG emissions.

2.2.1.1.2 CBA approaches

The literature suggests that there are four main approaches to CBA, namely net present value (NPV), cost-benefit ratio (CBR), internal rate of return (IRR), consumer surplus and producer surplus approaches. These are described below:

- NPV

The net present value (NPV) of an investment reflects the profitability of a project assessed over the defined life of the project and is determined by subtracting the discounted costs from the discounted benefits of the project (Kumar et al., 2015). The discounted benefits represent the value of all future benefits discounted back to the present time, while the discounted costs express the value of all future costs discounted back to the present time. The NPV approach is given mathematically by Eq. 2-1. A positive NPV indicates that an investment is justified economically at the given discount rate, and vice versa.

$$\text{NPV} = \sum_{j=0}^{n-1} \frac{a_j - b_j}{(1 + k/100)^j} \qquad Eq. 2-1$$

in which n is the analysis period in years; j is the current year, with $j = 0$ as the base year; a_j is all benefits in year j; b_j is all costs in year j; and k is the discount rate.

- CBR

The cost-benefit ratio (CBR) (or profitability index) indicates (a.) whether or not an investment can be profitable and (b.) the degree to which the investment can profit (Mishan and Quah, 2007). It is calculated via taking the NPV of expected future cash flows from the investment and dividing by the investment's original cost. The ratio that takes a value greater than one means the investment is profitable while its value taking less than one means the investment is non-profitable.

- IRR

The internal rate of return (IRR) is the discount rate such that the discounted benefits are equal to discounted costs over a defined period of analysis (i.e., NPV = 0) (Robinson, 2008). The project amongst all alternatives with the highest IRR is usually taken as the preferred option. The IRR approach is given by Eq. 2-2. Compared to the NPV approach, an advantage of the IRR approach is that it does require the discount rate to be known, which is sometimes uncertain in the NPV approach. However, there is an assumption in the IRR approach that all incoming cash flows in the investment are re-invested, which does not happen in real life.

Despite this shortcoming, the IRR approach has been widely used to appraise investments in road transport projects.

$$\text{IRR} = \sum_{j=0}^{n-1} \frac{a_j - b_j}{(1 + k/100)^j} = 0 \qquad Eq. 2-2$$

- Consumer surplus approaches

The consumer surplus approach focuses on a certain kind of benefit – that is, whether the price a consumer pays for a service, or product, is lower than the price he or she would be willing to pay (Brent, 2006). The focus of the application of the consumer surplus approach for the evaluation of road transport projects is on road users' saved costs generated via road investment (Van der Tak and Ray, 1971). With reference to Fig. 2-1, C1 and C2 are the road users' cost before and after road investment, thereby the difference between C1 and C2 is a cost reduction following investment. T1 and T2 are the number of trips before and after investment, thus, the difference between T1 and T2 is the increment of the number of trip following investment (this difference is referred to as a generated traffic, i.e., extra traffic produced by road investment). Therefore, the demand curve indicates that a road users' cost that is decreasing leads to the gradual increment of the trip. Consequently, the calculation of the red triangular area under the demand curve bounded by C1, C2, T1 and T2 through Eq. 2-3 is the user costs saved after the road investment.

$$\text{Benefits} = \frac{(C1 - C2)(T1 - T2)}{2} \qquad Eq. 2-3$$

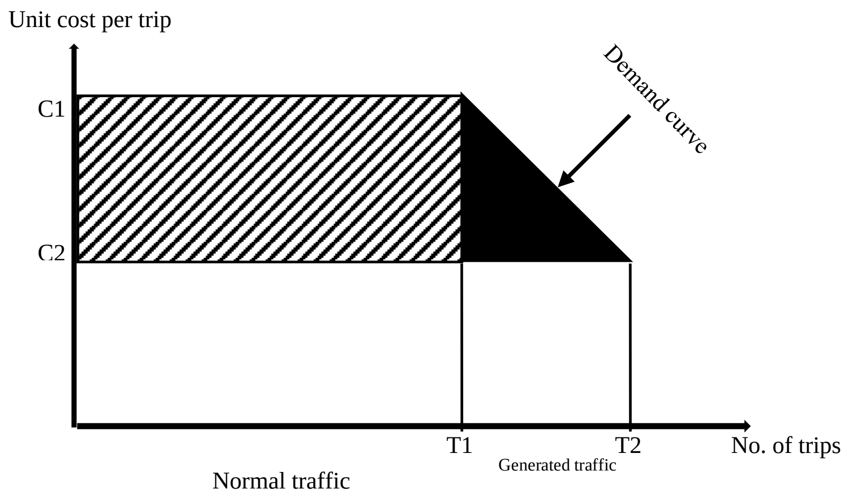


Figure 2-1: A demand curve to assess generated traffic benefits (source: Robinson, 2008)

- Producer surplus approach

The producer surplus approach is associated with the difference between the price a producer sells a good compared to the price at which he or she would be willing to sell the good (Robinson, 1999). For rural communities it is mostly associated with the benefit of road investment on the price of agricultural goods (Hine et al., 2015). In these circumstances the producer surplus approach considers the increment of farm-gate prices received by agricultural producers as the benefit of road investment, and is calculated by the price reduction multiplied by the volume of production (Carnemark et al., 1976; Beenhakker and Lago, 1983).

However, this approach has various shortcomings. Firstly, road investment is not the sole contributor to the net increase in agricultural production, for example irrigation or fertilizer can also contribute to this increment (Hine et al., 2000). Secondly, the approach has the problem of double counting. A reduction in transport costs to normal traffic (i.e. traffic which would pass along the existing road if no investment took place, including normal growth) is not separable from a rise in agricultural output. Thirdly, the approach fails to consider other benefits to the local community, such as an increased rate of school and medical attendance, and a higher number of trips to the local market due to improved access (Bovill, 1978; Hine et al., 2000; Van de Walle, 2002). Fourthly, this approach needs a large amount of data due to the consideration of many parameters (Beenhakker and Lago, 1983).

2.2.1.2 Multi criteria analysis

Multi criteria Analysis (MCA) has been widely applied for road investment appraisal by analysing the contribution of criteria to an investment (a criterion is a factor on which the judgement of an investment is based) (DCLG, 2009).

Compared with CBA, MCA can take into account criteria in monetary and non-monetary terms. This makes it possible to consider economic and non-economic (such as social, political, and environmental) impacts together (Robinson, 1999; Odoki et al., 2015). Thus, MCA can include the monetary analysis undertaken by CBA (Gühnemann et al. 2012), and it can also handle either qualitative data or quantitative data, alone or combined, in an appraisal (DCLG, 2009). Therefore, MCA is more flexible and comprehensive than CBA alone, and it enables road investment evaluation to consider more criteria than CBA does. Accordingly, its utilisation may facilitate the development of infrastructure sustainability (defined as infrastructure characterised by cost effectiveness and physical resilience (e.g. road pavement withstanding the impact of extreme weather in the context of the changing climate), social equity (e.g. a road network accommodating all users, including those with disabilities, low income, etc.), and environmental viability, so as to achieve current and future needs (National Research Council of the National Academies, 2009)).

Section 2.2.1.2.1 describes five specific MCA techniques and the criteria they take into account for road investment appraisal.

2.2.1.2.1 MCA techniques and corresponding criteria considered for road investment appraisal

According to Belton and Stewart (2002), three types of MCA models are particularly useful for ranking purposes (such as the ranking of road investments). The first type is (a) value measurement models that give each alternative a numerical value so as to denote the degree to which an alternative is preferred to another. The second type is (b) goal, aspiration, or reference level, models that can rank alternatives based on the distance from the alternatives to pre-defined goals or aspirations. The alternative that is closest to reaching the goals is assumed to have the highest priority, and so on. Lastly, the third type is (c) outranking models that are based on pairwise comparisons of alternatives against each other (or against a pre-defined norm) on each criterion through which the relevant evidence can be obtained to indicate that one alternative should be favoured over another. In general, the three kinds of MCA models incorporate the steps of (a) identifying criteria, (b) developing measurable indicators relating to criteria, (c) assigning weights to these indicators, and (d) composing the indicators (Beria et al., 2012).

Through relevant literature review, five MCA techniques that might be particular suitable for transport project assessment were identified via Tsamboulas et al. (1999). These are Analytic Hierarchic Process (AHP), Multi Attribute Utility Theory (MAUT), Technique for order preference by similarity to an ideal solution (TOPSIS), VIKOR (from the Serbian Vlse Kriterijumska Optimizacija Kompromisno Resenje, which means multi-criteria optimisation and compromise solution) and Elimination and Choice Expressing the Reality (ELECTRE).

AHP (also called MAUT variant) and MAUT are value measurement models, while ELECTRE is an outranking model, and TOPSIS and VIKOR are goal, aspiration, or reference level models. The strengths and weaknesses of the five techniques are summarised in Table 2-1 and further details of the techniques are given below. Chapter 4 considers the suitability of these techniques for the requirements of this research in more detail and describes a number of criteria that are used select the most appropriate.

Table 2-1: The strengths and weaknesses of the five identified MCA methods

Method	Strengths	Weaknesses	References
AHP	• Easy and convenient to obtain the weights of criteria by pairwise comparison • No need for a utility function to value criteria	• Consistency may not be guaranteed if many criteria need to be considered • Cannot provide information revealing incomparability between two alternatives	Ortiz-Garcia et al. (2005); DCLG (2009); Chen (2012); Figueira et al. (2013);
MAUT	• Can consider uncertainty • Can produce utility assigned to every possible consequence of the alternatives considered • Can generate accurate results	• Cannot provide information revealing incomparability between two alternatives • The need to develop a utility function for criteria is impractical when many criteria must be considered • Intensive data requirement	Ortiz-Garcia et al. (2005); Konidari and Mavrakis (2007); Figueira et al. (2013); Velasquez and Hester (2013)
TOPSIS	• Good computational efficiency • Comprehensibility • Can provide a complete ranking of alternatives	• The reliance on subjective expert opinion may result in deviation from reality • May cause a rank reversal that violates the invariance principle of utility theory	Roszkowska (2011); Garcia-Cascales and Lamata (2012); Fancello et al (2019); Ramasamy et al (2020)
VIKOR	• Can be used if the decision makers are unable to express their preference at the beginning • No need for interactive participation of decision makers when performed	• May not provide complete ranking of alternatives	Sayadi and Shahanaghi (2009); Kabir (2013); Kabir et al (2014); Fancello et al (2019)
ELECTRE II, III and IV	• ELECTRE IV does not require the calculation of weights of criteria • Can address (a) the imperfect knowledge of data and (b) the arbitrariness related to the construction of criteria	• May cause rank reversal • Difficulty in assigning a score to each alternative • The development of concordance and discordance indices needs some iteration, which is undesirable • It is relatively difficult to explain their processes and results in simple terms	Ortiz-Garcia et al. (2005); Konidari and Mavrakis (2007); Figueira et al. (2013); Govindan and Jepsen (2016);

a. AHP technique

The analytical hierarchy process (AHP) enables the analysis of a problem, particularly a complex problem (such as a multi criteria problem), by disaggregating the problem into a series of more understandable problems (i.e. sub-problems, sub-sub problems, etc.) using a hierarchical structure. Those problems on each level of the hierarchical structure are typically referred to as criteria (Saaty, 1980). Mathematically, the AHP is based on the linear additive model (referring to a combination of the values of criteria in an additive manner) (Tsamboulas, 1999; DCLG, 2009). Briefly, the value score of each criterion multiplies the weight of that criterion, which is calculated by pairwise comparison (see Chapter 4). Thereafter, all weighted scores are added together to obtain the total weighted score (i.e. the output of this analysis). The calculated weights of all criteria considered (i.e. a pairwise comparison matrix) are needed to check comparison's consistency using a consistency ratio (CR) (Saaty, 1980). The CR is the ratio of the consistency index (CIN) and random consistency index (RI), and should not exceed 10%. The CIN is dependent upon the maximum eigenvalue of the pairwise comparison matrix, and the RI is associated with the number of criteria. The limit of 10% represents the maximum tolerance allowed by human preference judgements for inconsistency. Further information about the AHP process is given in Chapter 4 and can also be found in Saaty (1980).

Bhandari et al. (2014) use AHP to rank four rural road sections in Dang district of Nepal via considering the impact of road investment in economic (such as construction cost, VOC etc.), social (population served, access to educational, health and other social services etc.) and environmental (such as the effect on natural system, possibility of landslide etc.) terms. Ahmed et al. (2017) also employ AHP to prioritise the maintenance of 28 road sections in different regions of Mumbai city in India. Other examples using AHP include road rehabilitation project ranking by Yadollahi and Rosli (2011), urban road pavement maintenance prioritisation by Prakasan et al. (2015) and transport infrastructure investment prioritisation by Quadros and Nassi (2015).

b. MAUT technique

Multi-attribute utility theory (MAUT) can analyse a multi-criteria problem by assessing the performance of the measurable criteria. Utility functions are typically developed to represent the degree of satisfaction with these criteria by utility scores. These are then aggregated into a total utility score (Velasquez and Hester, 2013; Dabous et al. 2019). Like the AHP, MAUT is also based on the linear additive model (Tsamboulas, 2007). Consequently, total utilities can be used as a basis for road investment appraisal. The main disadvantage of MAUT is that it necessitates the definition of marginal utility functions for each indicator of value and this is a non-trivial task if a great number of criteria need to be considered for a specific problem such as it is required for this research (Ortiz-Garcia et al., 2005; Moran et al., 2017).

Despite the weaknesses of MAUT, it is widely used to include more criteria within road investment related decision-making process. For example, Mohan et al. (1985) utilise MAUT to quantify traffic, climate, geometric standards, structural adequacy and type of subgrade soil for pavement condition evaluation. Using this process Mohan et al (1985) evaluate the impact of these factors on pavement condition, and determine the overall conditions of candidate pavement sections. The conditions determined are used as a basis for prioritising the rehabilitation for the pavement sections.

Abu-Samra and Zayed (2017) also use MAUT to develop a pavement condition rating model where utility functions are established to quantify climate conditions (such as pavement temperature, rainfall amount and freezing temperature), physical properties (such as surface and base layer depth, pavement age) and operational conditions (such as average daily traffic, rutting and transverse cracking amount). The outcome of the model provides the basis for the selection and prioritisation for road activities.

Zietsman et al. (2006) employ the MAUT approach to measure travel rate, accident rate, point-to-point travel cost, pollutant emission and fuel consumption. Based on the analysis, the need and appropriateness of widening road sections are determined.

c. TOPSIS technique

TOPSIS developed by Hwang and Yoon (1981) is a technique used to evaluate the performance of investments based on their similarity to an ideal solution, and to then rank investments by their performance (Fancello et al., 2019). The ideal solution comprises (a) a positive-ideal solution (PIS) maximising the benefit criteria and simultaneously minimising the cost criteria, and (b) a negative-ideal solution (NIS) maximising the cost criteria and simultaneously minimising the benefit criteria (Krohling and Pacheco, 2015). The investment with the highest performance (i.e. optimal point) will be closest to the PIS and farthest from the NIS, while the investment with the worst performance will be closest to the NIS and farthest from the PIS.

Through reviewing the relevant literature, several studies related to TOPSIS based road investment are identified. For example, Chen et al. (2015) developed a TOPSIS based methodology to establish a road safety risk index considering human factors (such as usage rate of seat belt and helmets), vehicle factors (such as usage rate of motorcycles and mopeds), road factors (such as road density), environment factors (such as percentage of urban population), management factors (such as annual number of speed violation notice per vehicle), personal risks (such as fatalities per road accident) and traffic risks (such as fatalities per 10000 vehicle). Chen et al. (2015) demonstrated the index by ranking 31 provinces in China.

Fancello et al. (2019) also use TOPSIS to set road safety priority intervention via considering (a.) sight distance from access (i.e., a non-obstacle view of the entire intersection and an amply view of the intersecting road); (b.) road signs and markings; (c.) lighting in intersection area; (d.) road surface condition (such as conditions of rutting, ponding etc.); (e.) density of traffic conflict points (i.e., conflict of trajectories of vehicle flow in the intersection area); (f.) number of vehicle entering the intersection area; (g.) the percentage of heavy vehicle; and (h.) pedestrian flow. Fancello et al. (2019) use this approach to rank six road intersections in Villacidro in Italy from the worst safety condition to the best. The worst safety condition has the highest priority for investment, the best has the lowest priority.

TOPSIS is also used to evaluate the effectiveness of alternative road investment projects by Rudzianskaite-Kvaraciejiene et al. (2010).

Although TOPSIS has been successfully applied to address road investment prioritisation in the road industry, Shih et al. (2007) suggests that TOPSIS is unable to deal with the relative importance (or weight) of criteria to be considered. Therefore, this technique was not considered further in this research.

d. VIKOR technique

VIKOR developed by Opricovic (1998) is a technique similar to TOSIS and is used to rank investments by measuring the ‘closeness’ to the ideal solution (Fancello et al. 2019). According to Opricovic and Tzeng (2004) and Sayadi and Shahanaghi (2009), the main difference between VIKOR and TOPSIS concerns the optimal point. TOPSIS is based on the principle that the optimal point has the closest distance to the PIS and is farthest away from the NIS. Hence, TOPSIS is more appropriate for decision makers who prefer to make as much profit and avoid as much risk as possible. In contrast, the optimal point in VIKOR is dependent upon the measure of closeness to PIS. Therefore, VIKOR is suitable for decision makers whose focus is on maximising profit rather than minimising risk.

In order to make a comparison between TOPSIS and VIKOR for road safety condition prioritisation, Fancello et al. (2019) uses VIKOR for the case study in Villacidro city as TOPSIS does, and the same criteria described in TOPSIS section are employed.

Babashamsi et al., (2016) also used VIKOR to rank pavement maintenance activities for three road pavement sections which have large maintenance needs in the east of Tehran in Iran via evaluating pavement condition index (PCI), operational time, improvement and maintenance costs, traffic congestion and pavement width.

Although VIKOR is successfully used to handle road investment prioritisation, it is not able to address issues related to the relative importance. Consequently VIKOR was not considered further for this research.

e. ELECTRE II, III, and IV techniques

ELECTRE II, III, and IV are three members of the ELECTRE family which can be used to rank investments (Opricovic and Tzeng, 2007; Figueira et al., 2013; Yu et al., 2018). In general, ELECTRE II, III, and IV provide a way to compare investment alternatives by means of criteria expressed by four outranking relations (Roy, 1991; Ortiz-Garcia et al., 2005). Further details regarding these four relations can be found in Vasto-Terrientes et al. (2015) and Figueira et al. (2013).

The difference between ELECTRE II, III, and IV is that the ELECTRE II only takes into account true criteria, whereas ELECTRE III and IV consider pseudo-criteria represented by a real valued function related to two threshold functions (Govindan and Jepsen, 2016). The main distinction between ELECTRE III and IV is that ELECTRE IV does not need to account for the weights of the criteria considered; as stated in Table 2-3, and is considered an advantage of the approach.

In order to compare the difference between ELECTRE II, III, and IV for ranking issue, Tsamboulas et al., (1999) employ them to rank three transportation infrastructure investments (i.e., investment a, b and c) considering three criteria, namely IRR of the investments, the reductions in accidents, and environment related issues (such as noise, air pollution etc.). For ELECTRE III, and IV, the result is $a < b < c$ ($<$ refers to the less priority than). For ELECTRE II, the result is $a < c < b$. Therefore, ELECTRE III, and IV were found to have different outputs compared to ELECTRE II.

2.2.2 Road asset management systems

Road asset management systems are designed to formalises activities (such as studies described in sections 2.2.1.1 and 2.2.1.2) related to the process of road asset management, namely maintenance, renewal, rehabilitation and reconstruction (Gharaibeh et al., 1999). Such systems are typically computerised and can support any or all of the three levels of road asset management described in Section 2.2. This section describes the functionalities of a typical road asset management system.

2.2.2.1 Functionalities for road asset management system

As stated by the UK Department for Transport (2013), a generic road asset management system encompasses several essential components as follows:

- Geographic Information System (GIS): spatial data related to road infrastructure assets. It enables the user to visualise road asset information and analyse the data presented within background mapping.
- Asset database: the asset database is a record of road assets including such as pavement structural databases.
- Maintenance management system: this system is able to support road maintenance management and typically compares road asset defects detected by safety inspectors with standards.
- Invoicing and payments: Invoicing and payments are linked to the maintenance management system in order to enable invoicing and payments to be made and auditable.
- Decision support systems: these systems typically include predictive modelling and can communicate with the asset database. Therefore, they can determine the future condition of an asset from which the relevant road lifecycle planning and road works programmes are developed.
- Asset valuation system: this system calculates metrics associated with valuing the asset. These can include measures such as the gross replacement costs (GRC) and depreciated replacement costs (DRC) through using information available in the inventory and the condition of the road asset provided by the asset database in order to determine.

Although a generic road asset management system includes the components above, the development of a road asset management system depends upon the preference of an organisation within they are implemented. For example, Gendreau and Soriano (1998) develop an airport pavement management system (APMS) consisting of several essential components, namely, network inventory, pavement condition evaluation, pavement performance prediction and management planning methods. Network inventory refers to an inventory of pavement network in the form of pavement sections representing the minimum portion of the network. The pavement network is divided into sections so as to show consistent characteristics (e.g. pavement structure, traffic volume etc.) and decisions on investments are made on a section by section basis.

The outcomes of pavement condition evaluation are inputs (i.e., current pavement condition) for decision process where investment related activities can be determined. Evaluation is typically associated with the structural (or bearing) and functional condition of the road network. Structural evaluation includes two sequential stages. First is to determine the physical characteristics of the materials of the pavement structure, and second is to analyse the impact of loadings on the structure for purpose of assessment of its deformation response (Zaniewski, 1991). Functional evaluation refers to the analysis of roughness and skid resistance, and is associated with the potential for foreign object damage to vehicles and cause surface distress (e.g. cracking, rutting, pothole, patching etc.) (Shahin, 1982). Data for such evaluation derives from direct measurements, visual condition surveys or their hybrid utilisation. Typically, such measurements could be expressed as a quality index indicating the state of the pavement deterioration at a specific time. A number of quality indices are described in the literature, including the Unified Pavement Distress Index (UPDI) (Juang and Amirkhanian, 1992), Overall Acceptance Index (OAI) (Zhang et al., 1993), Overall Pavement Condition Index (OPCI) (Shah et al., 2013), and Pavement Distress Condition Index (PDCI) (Zhou et al., 2014).

Pavement performance predication models are used to predict the future pavement performance. Models could be either deterministic or probabilistic (Butt, 1991). The former can predict the remaining life of a pavement or level of distress on the pavement using an exact number. Therefore, it takes into account the progression of pavement deterioration over time. The latter predict the diverse possible future conditions as pavement deterioration is regarded as a stochastic process, i.e., the deterioration process is somewhat uncertain and thereby not amenable to exact predication (see Section 2.3). Often probabilistic models are based on historical measures of road condition.

Finally, management planning module can determine the appropriate road investment related action given current and future condition of pavement sections. At the project (operational) level, decisions are related to when a pavement section should have an investment intervention and what intervention should be carried out, while decisions are related to where, when and what investment interventions should be undertaken at the network level (i.e. strategic and tactical levels of road asset management) (Butt, 1991).

2.3 Uncertainty within road asset management

According to Özkan and Türksen (2014), uncertainty is a concept related to a human being's abilities, capacities, intuition and perception. For example, the amount of precipitation tomorrow judged by our intuition, abilities or capacities normally involves uncertainty, i.e., the judgement's correctness is doubtable. Therefore, failure to take into account uncertainty may lead to the problems in terms of validity and accuracy (Preston et al., 2011).

In essence, there are two kinds of uncertainties, namely, aleatoric and epistemic uncertainties. They could be respectively expressed by probability distribution function (PDF) (Nilsen and Aven, 2003) or a membership function (MF) (Ross, 2005). A PDF indicates the probability of all the possible values a parameter may take, while MF the membership degree of each value within the range a parameter may take. More detail can be elaborated below.

2.3.1 Aleatoric uncertainty

Aleatoric uncertainty refers to uncertainty regarding something due to its irregular pattern (or randomness) (O'Hagan et al., 2006). The review of the literature has shown that the Markov chain approach has been widely used to address uncertainty within road asset management. For example, Gendreau and Soriano (1994) utilise the Markov chain to model the change of the state of pavement condition transitioning from 'very good' to 'very bad'. The nature of such a transition is a stochastic process and a probability density function (PDF) is utilised to represent the probabilities of possible states. For example, Kulkarni (1984), Butt et al. (1987) and Gendreau and Soriano (1994) developed a Markovian model for predicting pavement performance so as to determine the road investment strategy. Such prediction is to estimate several probable transitions to future pavement states from current state. Costello et al. (2005) also developed a Markov-based stochastic model for assessing road maintenance funding and policy decisions. Saha et al. (2017) developed Markov-chain-based model to establish five distress indices, namely, fatigue, transverse and longitudinal rut and ride indices. Through the predicated distribution of indices, the path for pavement deterioration can be obtained (e.g. very good condition → fair).

According to Kulkarni (1984), a Markovian predication model has several advantages (a.) road preservative investment strategy it generates is based on the future pavement performance rather than being pre-determined; (b.) road investments in the immediate future or the next few years can be identified; (c.) it could save costs by selecting less conservative intervention where the prescribed performance standards are still satisfied. However, Gendreau and Soriano (1994) suggest the requirement for a large amount of historical data (e.g. data for pavement condition index) to operate Markov chain as a drawback.

In addition, to the Markov chain, Monte Carlo (MC) simulation, as a random number generator, can be used to deal with aleatoric uncertainty using a PDF (Loyd, 2004). For instance, Dadashi and Mirbaha (2019) use the PDF to express the range of values parameters may take (e.g. cost of the project) in their proposed model, thereafter, the MC method is employed to randomly produce a sufficient quantity of specific values for parameters. This procedure also generates an adequate number of random cases for output. Such output is utilised to prioritise highway safety improvement projects.

Li et al. (2020) also use MC method to simulate a large number of disaster samples, including probable disaster scenarios (i.e., road link failure due to landslide, debris flow), recovery actions and traffic assignment, in the development of a resilience analysis framework. Through such simulation, Li et al. (2020) analyse road network performance in an extreme environment. They use their model to analyse (a.) mobility and accessibility at road network level, (b.) ratio of post-disaster traffic flow to pre-disaster traffic flow at road link level. Mobility refers to the ratio of the all the users' average travel time before disaster to the average travel time under the simulated disaster scenarios. Accessibility is the ratio of satisfying travel demand in the context of all the simulated disaster scenarios to the totality of travel demand. Based on this, the relevant optimisation strategies (e.g. strengthen the capacity of a road k) are proposed to facilitate the improvement of the resilience of road network. MC method is also employed by Yang and Frangopol (2019) to simulate the possible future scenarios for climate change and socioeconomic growth (e.g. increase in population) for a robust traffic assessment. Kim and Li (2020) use MC to simulate the possible river open days for river barge freight resulting from a changing climate for supporting the construction of all-weather Mackenzie Valley highway in Canada.

In spite of the wide application of MC method, determining a specific PDF for a domain problem, especially the value of its parameters (e.g. mean and standard deviation), without relevant data is a challenging. Consequently, expert opinion is often employed (Grigore et al., 2013). However, expert opinion also brings about problems, such as uncertainty for estimating the values of PDF parameters (O'Hagan et al., 2006).

2.3.2 Epistemic uncertainty

As suggested by O'Hagan et al. (2006), epistemic uncertainty refers to uncertainty for something because of imperfect knowledge. thereby, it is reducible (Dutt and Kurian, 2013). Normally, epistemic uncertainty could be viewed as vague (i.e., no specific) or fuzzy (i.e., unclear or not sharp) uncertainty. The former is related to the description of an object without considering its unit (such as given a "the whale is heavy", "heavy" does not relate to a unit of weight such as grams, kilograms or tonnes), while the latter considers the units (such as "the whale is approximately two tonnes"). As suggested by Zadeh (1995), vague uncertainty is considered to be fuzzy, but the reverse is not true.

MF could be used to model vague and fuzzy uncertainties. The shape of the MF (e.g. triangular MF) depends upon the domain problem and the MF's parameters could be based on expert opinion which is straightforward to obtain. For example, an expert could relatively easily estimate a whale's weight via natural language, such as approximately two tonnes. Based on this, a membership function could be developed to express "approximately two tonnes". Such a description of weight is regarded as a fuzzy set (see Appendix A) characterised by a membership function expressing every specific weight within the set regarding "approximately two tonnes" together with its membership degree to the set ranging between 0 and 1. 0 represents the incomplete membership of a specific weight to the set, while 1 the complete membership of a specific weight to the set. Fuzzy reasoning and MFs are discussed further in Section 4.3.

The literature review found a number of applications of MF for the road industry. For example, Filippo et al. (2007) and Moazami et al. (2011) take advantage of MF to express parameters considered for road investment prioritisation. The former considers parameters related to (a.) accident risk (e.g. proportion of the highway with defects on the road surface, such as corrugation, potholes etc.), (b.) social and economic importance (e.g. average daily traffic volume travelling on the highway), (c.) environmental sensitivity (e.g. the proportion of the highway running through the conservative area) and environmental impacts (e.g. the number of environmental liabilities, such as area degraded by erosion, flooding), and risk of erosion, landslip and landslide (e.g. the proportion of the highway running through such as mountainous terrain). The latter take into account parameters including the pavement condition index, road width, traffic volume and cost of maintenance and rehabilitation. EL-Rashidy and Grant-Muller (2015) employ MF to express (a.) physical connectivity and (b.) traffic condition for assessment of road transport network mobility. An MF is used by Pan (2005) to express the amount of precipitation and loss of productivity related to highway construction activities in order to estimate the duration of a highway project. Martín et al. (2016) use an MF to represent the lane width, road surface condition and the amount of rainfall in order to determine the level of service of two-lane roads.

In addition to the application of MF in parameter uncertainty, a number of road related studies were found that utilize fuzzy AHP to determine the relative importance of parametres. For example, Ouma et al. (2015) and Babashamsi et al. (2016) use fuzzy AHP to calculate the weights of criteria including the pavement condition index, traffic congestion, pavement width road safety and pavement surface condition. Fuzzy AHP is used by Gülgen (2014) to determine weights for the development of road hierarchy structure (in terms of road class, length and centralities of degree, closeness) and for determining road handling priority for road links by Wedagama (2010) and road safety analysis by Kanuganti et al. (2016).

2.4 Summary

This chapter defined asset management in terms of three levels, namely strategic planning, programming and operational levels. Road asset management investment appraisal approaches were discussed. These included CBA and MCA. CBA was shown through the consideration of criteria in road investment projects/programmes and the specific CBA methods (e.g. NPV), while MCA was demonstrated via several MCA methods (e.g. AHP) and corresponding road investment criteria considered. The road asset management system was described in terms of its functionalities.

Two forms of uncertainty were considered, i.e., parameter uncertainty and uncertainty related to expert elicitation. The literature review found a number of road asset research related studies which used PDFs together with Markov modelling and Monte Carlo simulation and MF in conjunction with fuzzy AHP to deal with such uncertainties. PDFs were related to aleatory uncertainty, while MF was associated with epistemic uncertainty.

The next chapter will review vulnerability assessment in order to gain an insight into risks for rural communities associated with lack of rural access.

CHAPTER 3 VULNERABILITY ASSESSMENT

This chapter consists of six sections. First, concepts related to vulnerability are described in section 3.1. Second, the vulnerability approaches/examples are demonstrated in section 3.2. Third, studies related to dealing with biophysical and social vulnerabilities are identified in section 3.3. Fourth, uncertainty within vulnerability assessment is handled in section 3.4. Fifth, the gap between road investment prioritisation and rural community road access vulnerability is identified in section 3.5. Sixth, a summary of the chapter is given in section 3.6.

3.1 Concepts relevant to vulnerability

3.1.1 The definitions of vulnerability

Many definitions of vulnerability have been proposed and can be categorised according to the following three dimensions:

- Biophysical vulnerability, which refers to the susceptibility of people, assets, or places to external hazardous events (for example, the occurrence of an extreme rainfall causes a road failure) (Mitchell (1989); Alexander (1993));
- Social vulnerability, which is the susceptibility to the impact of a hazardous event due to lack of societal resistance or resilience (Timmerman (1981); Susman et al. (1983); Burton et al. (1985); Bogard (1989); Chambers (1989); Downing (1991); Dow (1992); Smith (1992); Watts and Bohle (1993); Blaikie et al. (1994); Bohle et al., (1994); Cutter et al., (2003)); and
- Combined biophysical and social vulnerability, which includes both susceptibility to hazardous events and lack of societal resistance or resilience to withstand hazardous

events (Cutter (1993); McCarthy et al. (2001); IPCC (2007); Turner et al. (2003); Adger et al. (2004); Adger et al. (2005)).

3.1.2 Categories of determinants of vulnerability

As stated by Preston et al. (2011), the vulnerability of a given asset, or system, can be determined via factors contributing to the potential for harm from external threats as well as the internal adaptive capacity of institutions, sectors, and communities. Generic determinants of vulnerability can be categorised as follows (Adger et al., 2004; Burrow, 2014).

- Biophysical determinants refer to the physical, biological, and ecological factors influencing the potential for harm. These factors might include climatic conditions, natural hazards, and topography.
- Socioeconomic determinants are the social, economic, or cultural factors influencing the potential for harm. Examples are demography, poverty, trade, employment, gender, and governance.

3.1.3 Risk assessment and vulnerability assessment

3.1.3.1 Risk assessment

According to the British standard for risk management, BS EN 31010:2010 (BSI, 2010), risk assessment is an approach to understand risks (referring to an event that is likely to occur and that results in loss), their causes, consequences, and probabilities. This assessment includes three sequential stages, namely risk identification, risk analysis, and risk evaluation. Specifically, risk identification refers to the process of finding, recognising, and recording risks. Risk analysis entails measuring the level of risk by estimating the consequences of an event and their related probabilities. Lastly, risk evaluation means decision-making with respect to future actions by taking advantage of the results of risk analysis.

3.1.3.2 Vulnerability assessment

According to the British standard for risk management, BS EN 31010:2010 (BSI, 2010), in some situations, the occurrence of a consequence is determined by a range of events, while in others, no specific event is identified. In such situations, the focus of risk assessment is switched to analysis of vulnerability of the components of the system at risk.

As there is little literature on standardised/universal procedures of vulnerability assessment, vulnerability assessment is defined herein as a way to understand vulnerability using vulnerability identification, vulnerability analysis, and vulnerability evaluation. Specifically,

- Vulnerability identification is a process of finding, recognising, and recording the determinants of a type of vulnerability – that is, the vulnerability of what to what.
- Vulnerability analysis refers to the measurement of identified determinants of vulnerability in a qualitative, semi-quantitative, quantitative, or hybrid manner.
- Vulnerability evaluation is a process of calculating the overall vulnerability value which can be used as a basis for making a decision on further actions.

3.1.3.3 Geographical scales in vulnerability assessment

According to Preston et al. (2011), the geographic scales in vulnerability assessment are arbitrarily divided into:

- Local geographic area that is related to an individual local government area or municipality.

- Regional geographic area that is related to a set of local government areas or catchments, in a single state or province.
- National geographic area that is related to an individual country.
- Continental geographic area that is related to an individual continent or cluster of nations (such as European continent).
- Global geographic area.

In this research, the assessment of rural community road access vulnerability is on the scale of local geographical area.

3.2 Vulnerability approaches/models

3.2.1 Examples of vulnerability approaches

The literature describes a number of examples of the use of vulnerability analysis. These are summarised in Table 3-1.

Table 3-1: Examples of vulnerability approaches in vulnerability research traditions (after Adger, 2006)

Vulnerability examples	***Description***	***Objectives***	***Dimension of vulnerability***	***Dimension of vulnerability determinants***	***References***
<u>Antecedents</u>					
Famine and food insecurity vulnerability	These approaches analyse vulnerability using an entitlement-based perspective. In general, entitlement refers to resources available to individuals based on their existing production or assets (see Chapter 5). Hence, the entitlement is the source of income.	To interpret the cause of this vulnerability by identifying disruptive entitlement or its complete failure and lack of capabilities.	Social vulnerability	Social determinant	Sen (1983); Swift (1989); Watts and Bohle (1993)
Vulnerability to hazards	These approaches analyse the vulnerability to hazards, i.e. biophysical vulnerability using the conventional risk-based methodology (See section 3.2.2.1).	To identify and predict which population groups or regions are vulnerable to hazards by analysing the determinants of biophysical vulnerability (or biophysical determinants) in such a way that the likelihood of hazards is combined with their consequences.	Biophysical vulnerability	Biophysical determinant	Burton et al. (1993); Smith (1996)
Human ecology	These approaches consider the structural and political factors leading to social vulnerability.	Identify structural and political factors to explain why the poor and marginalised are most often at risk when hazards occur.	Social vulnerability	Social and economic determinants	Hewitt (1983); Mustafa (1998)
Pressure and release	These approaches link biophysical vulnerability to social vulnerability.	Gain deeper insight into the human ecology approach by considering hazards risk.	Biophysical and social vulnerability	Biophysical and social determinants	Blaikie et al. (1994); Singh (2014); Awal (2015)

Successors					
Climate change and variability vulnerability	This approach focuses on the vulnerability to future risks associated with climate change and variability.	To explain why the physical, biological, or social system is susceptible to future risks.	Biophysical vulnerability	Biophysical and socio-economical determinants	Ford and Smit (2004); Nelson et al. (2010);
Sustainable livelihoods and poverty vulnerability	This approach associates the risk with well-being (i.e. a source of income) at an individual level. This complements the approach of vulnerability to hazards.	To interprets the reason why populations are becoming or staying poor by analysing economic factors and social relations.	Social vulnerability	Social and economic determinant	Morduch (1994); Bebbington (1999); Ellis (2000); Dercon (2004)
Vulnerability of the coupled human and environmental system	This approach deals with the vulnerability of a coupled human and environmental system by mainly considering exposure, sensitivity, and resilience (see Section 3.2.2.4 and Chapter 5).	To explains the vulnerability of this coupled system as comprehensively as possible.	Biophysical and social vulnerability	Biophysical and socio-economical determinants	Luers et al. (2003); Turner et al. (2003)

In this research, the coupled human and environmental system focused vulnerability approach was used in order to widely understand why a rural community is vulnerable to the disruptive access due to deteriorated or/and impassable roads serving the rural community, i.e., the rural community road access vulnerability.

3.2.2 Vulnerability models

In general, the vulnerability approaches described above can be categorised in terms of four types of models, namely Risk-Hazard (RH) models, Social Vulnerability (SV) models, Pressure and Release (PAR) models and Expanded Vulnerability (EV) models.

3.2.2.1 Risk-hazard models

Risk-hazard (RH) models focus on biophysical vulnerability (i.e. the components of biophysical vulnerability: hazards and exposure to hazards), and they correspond to the previously discussed hazards vulnerability approach. RH models were developed to determine the impact of a hazardous event based on the exposure to this event together with the sensitivity of an exposed system (e.g. a rural community). This is diagrammatically represented in Figure 3-1 (Turner et al., 2003; Preston et al., 2011). However, the sensitivity to the impact is not analysed even if it is recognised (Turner et al., 2003). Typically, a hazard may be a geo-hazard such as flood, landslide etc., while the relative density of the exposed assets (e.g. population or development density) can be used to express sensitivity. As a result, from a methodological standpoint, these models take advantage of a conventional risk-based methodology, where vulnerability is considered to be a combination of the likelihood of exposure to the hazardous event and the consequence of the exposure (see Section 3.2.1). The former is most often quantitatively expressed as a frequency of occurrence of exposure, while the latter is related to a form of loss expressed in either a numerically quantifiable or unquantifiable manner (Burrow, 2014). The vulnerability approach mentioned in section 3.2.1 uses RH models to scrutinise road networks' vulnerability to disruption.

In a comparative study of 45 climate change vulnerability-based models, Jones et al. (2011) identified 14 studies using RH models. For example, Karim and Mimua, (2008) and Sharples et al., (2009) use RH model to analyse coastal vulnerability. Bayliss et al., (1997) use it for vulnerability to predict climate change and sea level rise. Doll (2009) for vulnerability to renewable groundwater resources affected by climate change.

Despite these applications, RH models are not capable of considering (1) the system's ability to cope with or adapt to the effects of hazardous events; (2) the characteristics of an exposed system which can cause considerable variation in consequences resulting from the occurrence of hazardous events; or (3) the impact of the social fabric and institutions on exposure to hazardous events and their associated consequences (Turner et al., 2003; Preston et al., 2011; Burrow, 2014).

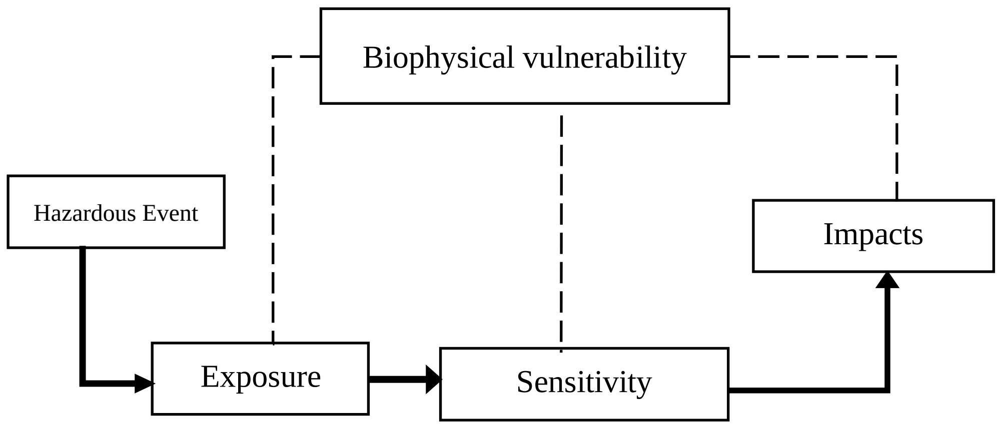


Figure 3-1: Risk-hazard models (source: Turner et al., 2003)

- Application of R-H models in road industry

Vulnerability approaches provide ways in which the concept of vulnerability (i.e. biophysical vulnerability (see Section 3.1.1)) can be utilised to scrutinise the vulnerability of an agent (in the case of this work: the road network). Road network vulnerability in the literature is not only defined in several ways, but also measured by different dimensions.

In terms of its definition, road network vulnerability refers to the susceptibility of a road network to incidents so as to significantly attenuate its capacity to serve traffics (or serviceability) (Berdica, 2002). Additionally, vulnerability could be associated with the non-operability of the road network in the context of certain situations (i.e. inability to retain its function) (Husdal, 2005). Although different terms (i.e. serviceability and non-operability) can be used to represent road network vulnerability, they could be regarded as approximately equivalent to the road network performance. For example, Nicholson and Du (1997) evaluate road network performance in terms of the performance of links (i.e., roads) within the network due to road works, congestion and accidents etc. Accordingly, road network vulnerability can be defined as reduced serviceability or operability of a road network (Jenelius et al., 2006).

In terms of its measurement, road network vulnerability technological and/or societal dimensions can be used (Jenelius, 2010). In terms of technological dimensions, vulnerability could be measured by either the consequence of the failure of the component(s), which is referred to as importance or conditional criticality (Nicholson and Du, 1994; Luathep et al., 2011; Rupi et al., 2015), or the combination of the failure probability and the importance (i.e., consequence) of the failure, which is referred to as criticality (Jenelius et al., 2006; Jenelius and Mattsson, 2012). From the societal perspective, the importance is replaced with exposure representing the impact of the failure on the individual user or stakeholder (Jenelius, 2010).

In the study by Rupi et al. (2015), vulnerability is considered to be analogous to the concept of importance, i.e. the more severe the consequence of the failure of a road link, the more important the road link is, then more vulnerable it is. Using this approach, the prioritisation of the maintenance of road links on a road network is based on the consequence of road link closure. The consequence of a road link blockage is composed of (a.) the number of people typically utilising the link, and (b.) the impact of this link closure on the general functionality of the whole network.

Similarly, Luathep et al. (2011) treat vulnerability as the consequence of the disruption of a road link, i.e. the impact of a road link's loss of capacity in socio-economic terms (e.g. the number of trips). In their work, Luathep et al. (2011) develop the accessibility index (AI) to represent an impact. The AI difference is given by the difference in AI between ideal network performance (i.e., no link is degraded or closured) and the degraded network state (where one or more road links has reduced functionality or is closed,). A link that has a large difference in AI between a normal and a degraded network is regarded as a critical link. Accordingly, the AI difference can be used to prioritise links, and the more critical a link is, the higher its priority for investment.

3.2.2.2 Social vulnerability models

Social vulnerability (SV) models, demonstrated in Figure 3-2, refer to a relationship between potential hazards and social structure to reflect social vulnerability. In other words, potential hazards generated by risk is either moderated or enhanced by elements within the social structure, such as demography, poverty, trade, and employment (Wu et al., 2002). Hence, SV models focus on socioeconomic determinants (such as) of vulnerability (or sensitivity), corresponding to the human ecology approach mentioned above. For example, adverse outcomes resulting from the occurrence of hazards may be determined by the characteristics of different populations, settlement types and locations, risk management practices, or cultural behaviours (Preston et al., 2011).

Many socioeconomic indicators of vulnerability have been proposed in the literature, encompassing gender (Blaikie et al.,1994; Enarson and Morrow, 1999), age (Hewitt, 1997; Cutter et al., 2000), race and ethnicity (Bolin, 1993; Bolin and Stanford, 1998; Pulido, 2000), family structure (Blaikie et al., 1994; Morrow, 1999), medical services/facilities (Hewitt, 1997; Morrow, 1999), education (HCSEE, 2000), and employment loss (Mileti, 1999). According to Baum et al. (2009), the development of mathematical models for these indicators is readily manipulated due to the large availability of datasets so that the SV models should be statistically robust. However, Preston et al. (2011) question the validity of using such coarse indicators to measure complex social and economic factors and human decisions in a threatened environment, noting that these indicators may simply be an artificial construct based on a priori assumption. Nevertheless, such data still play an important role in the recognition of the significance of social vulnerability, particularly when they are used in context with a wider understanding of the localised social vulnerability issues of the systems being considered (Barnett et al., 2008).

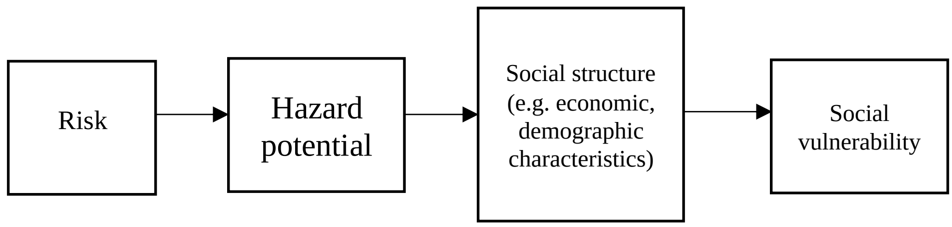


Figure 3-2: Social vulnerability models (source: modified from Cutter et al., 2003)

3.2.2.3 Pressure and release models

Pressure and release (PAR) models combine RH models with SV models, thus considering both biophysical and social vulnerabilities and involving the components of exposure to hazards, sensitivity, and adaptive capacity (Preston et al., 2011). PAR models offer a way to understand risk as a disaster triggered by the interaction of a specific hazard with social vulnerability. Hence, risk according to the PAR model (see Figure 3-3) can be formulated as

$$\text{risk} = \text{hazards (or biophysical vulnerability)} \times \text{social vulnerability} \qquad Eq. 3-1$$

Specifically, PAR models demonstrate that disaster is associated with hazards and vulnerability, i.e., the occurrence of hazards within the context of the unsafe condition leads to disaster. The former can be climatological (e.g. flood, drought), biological and ecological (e.g. landslide, soil erosion) and so on. The latter includes three sequential stages, namely root cause, dynamic pressure, and unsafe conditions. Specifically, root cause derives from economic, demographic, and political processes during which several population groups receive unfair allocation and distribution of resources. Dynamic pressure provides a channel for transforming the effects of root cause into unsafe conditions. Unsafe conditions are the specific forms in which the vulnerability of the exposed system is expressed in time and space.

Although PAR models are more holistic than RH and SV models, it is still difficult to clarify the degree of contribution of biophysical and social vulnerabilities to overall vulnerability, making an arbitrary conclusion inevitable (Preston et al., 2011; Burrow, 2014). This is because PAR models do not explicitly define the relationships between coupled human and environmental systems. Nonetheless, a number of studies have used PAR models to assess vulnerability. Jones et al. (2011) found that PAR models used vulnerability assessment in 23 out of 45 (51%) studies they analysed. On a global scale, among these studies, Yohe et al. (2006) measure education, wealth, resource access, and population, among others, to express biophysical and social vulnerability for the purpose of mapping the global distribution of climate change vulnerability. Furthermore, Yusuf and Francisco (2009) map several nations' and sub-national regions' vulnerability to climate change in the Asia-Pacific region. At the municipal or local level, Wu et al. (2002) and Kleinosky et al. (2007) assess vulnerability to sea level rise by using several social indicators, such as race and age. Preston and Jones (2008) examine vulnerability to climate change related hazards in coastal areas in Sydney, Australia based on six biophysical and socioeconomic and natural resource management risk indicators. Finally, Vescovi et al. (2005) and Baum et al. (2009) investigate human health vulnerability to extreme heat events.

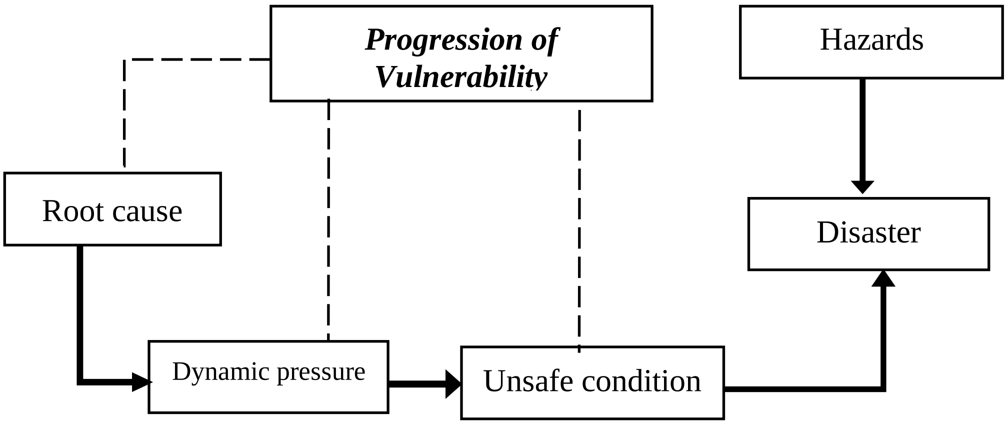


Figure 3-3: Pressure and release models (source: Blaikie et al., 1994)

3.2.2.4 Expanded vulnerability models

Expanded vulnerability (EV) models, such as that shown in Figure 3-4, mainly focus on the biophysical and social vulnerabilities of a coupled human and environmental system. They involve components of exposure (i.e. exposure to hazardous events), sensitivity (i.e. sensitivity to exposure), and resilience (i.e. the ability to withstand exposure) (Turner et al., 2003). Human and biophysical processes operating in this coupled system interact with each other, so the biophysical vulnerability of the environmental system, for instance, can be impacted by the human response to hazards, e.g. an improvement in the drainage, such as a side ditch, of a paved road may keep the road serviceable even if there is extreme rainfall (Burrow, 2014).

Briefly, analysing the vulnerabilities of a coupled system using EV models entails several essential components: (a.) a perturbation and stress/stressor (for instance, geo-hazards which would affect the road access of rural communities are regarded as perturbations and stress/stressors (Burrow, 2014)), (b.) the exposure to the perturbation or/and stress/stressor, (c.) the sensitivity of the coupled systems to the exposure, (d.) the resilience of the coupled system to the exposure (i.e. coping or response), (e.) the reconstruction of the system after the response or coping (i.e. adjustment or adaptation), and (f.) nested scales (e.g. world, region, and place) and scalar dynamics of hazards, coupled systems, and their responses.

EV models' applications are limited by their complexity in terms of (a.) representing complex interactions between vulnerability determinants, (b.) the large amounts of data required, and (c.) the nested temporal and spatial scales. Nevertheless, several researchers have used these models for vulnerability assessment. For example, Willroth et al. (2011) use an EV model to analyse the vulnerabilities and the development of adaptation strategy in the villages of Khao Lak and Ban Nam Khem in southern Thailand. They find that social networks are a pivotal determinant for coping with disaster, while social cohesion is the kernel of the development of adaptation strategies.

The air pollution vulnerability models developed by John et al. (2008) consider biophysical and social vulnerabilities through EV models. Specifically, biophysical vulnerability refers to exposure to air pollution, while social vulnerability describes susceptibility to the exposure and is determined by demographic factors (e.g. age, gender) and socioeconomic conditions. However, some socioeconomic conditions that help in coping with the impact of exposure and susceptibility are treated as adaptive capacity. Thus, their model focuses on explaining why a unity (e.g. a population group) is vulnerable to air pollution based on three components: namely, exposure, susceptibility, and adaptive capacity (See Figure 3-5).

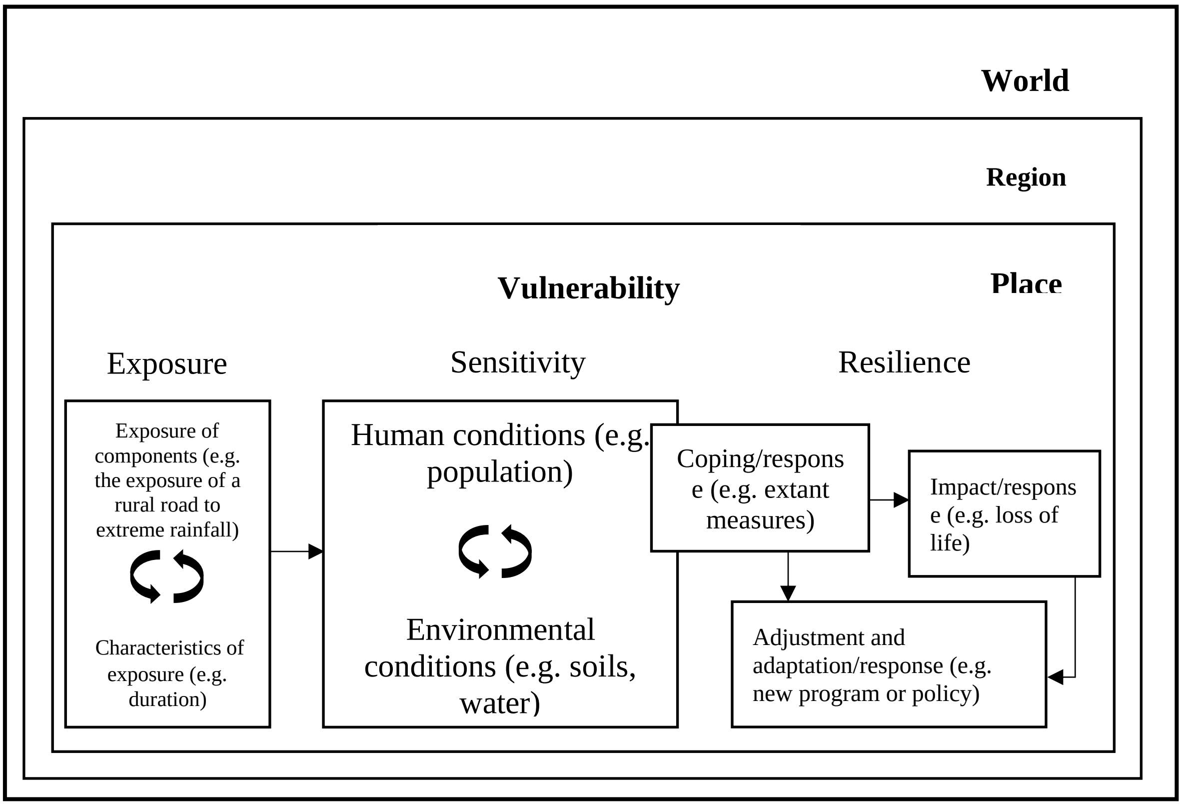
Avis and Khaemba (2018) used the models developed by John et al. (2008) to analyse the vulnerability to air pollution in East Africa. The determinants of this vulnerability that they identify are given in Table 3-2.

Table 3-2: Vulnerability components, high risk groups identified from the literature (Avis and Khaemba, 2018)

Vulnerability component		**Population characteristics and associated factors that contribute to vulnerability**			
	Age	Disease or poor health status	Gender	Time-activity patterns	Socio-economic conditions
Susceptibility	Physiological immaturity Physiological effects of ageing Pre-existing diseases Nutrition	Comprised organ functions Diminished ability to homeostasis	Physiological differences Pregnancy		Health and other services Nutrition Work Smoking
Exposure	Mobility, confinement Height Exploratory behaviours and playing Outdoor and indoor activities		Outdoor and indoor activities Domestic activities Work	Outdoor and indoor activities Transport Residential location Housing quality Work	Risk management options Health and other services Public information and health education Social networks Risk mitigating technologies
Adaptive capacity	Isolation Dependence on caregivers		Risk perception Health management practices		
Population groups identified in the literature					
	Children, foetuses, infants, adolescents,	Elderly Children Young adults	Pregnant women Young women	Commuters Residents near high traffic areas	Poor and low-income persons

	Elderly	Socio-economically deprived persons		Children Young adults Persons physically active outdoors Workers, traffic, blue collar	Poorly educated persons Elderly and socially isolated persons Racial and ethnic minorities

Figure 3-4 : EV model (source : Turner et al., 2003)



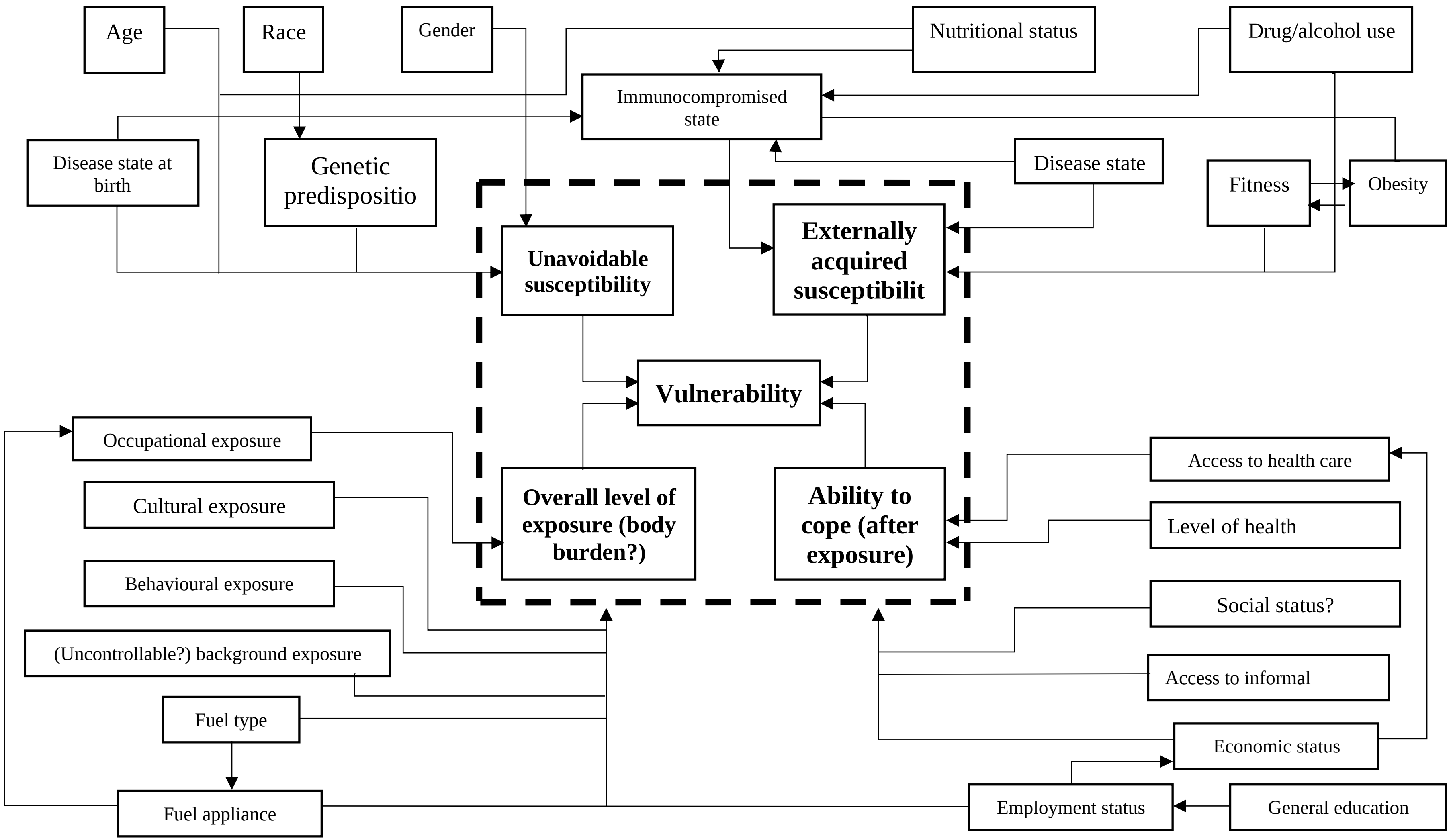


Figure 3-5: Air pollution vulnerability model (Source : John et al., 2008)

3.3 Studies addressing biophysical and social vulnerabilities

This section describes studies addressing biophysical and social vulnerabilities in sections 3.3.1 and 3.3.2 respectively.

3.3.1 Studies addressing biophysical risk

The literature review found several studies associated with the biophysical risk of roads to geo-hazard. The studies focused on the assessment of either the likelihood of the occurrence of geo-hazards and / or the severity of the impact of the geo-hazard. For example, Blais-Stevens and Hungr (2008) assess the frequency of the occurrence of several kinds of landslides (i.e., rock falls, rockslides, debris flow and submarine landslides) in areas along or adjacent to highways. Kalantari et al. (2019) assess the probability of flooding by considering physical watershed characteristics (such as size, elevation etc.), and soil moisture. Lee et al. (2018) also assess regional landslide likelihood so as to inform which road sections are highly susceptible to landslide hazards. With respect to severity, Federal Highway Administration (2011) develops a five-level rating system to assess the severity of the influence of geo hazards on highways.

A useful summary of the impacts of geo-hazards on road infrastructure is provided by Argyroudis et al. (2019). In their study, they note that road infrastructure assets, as a combination of interdependent assets (i.e., System of Assets (SoA)), could be exposed to more than one geo-hazard and suggest that there is the absence of relevant researches. The work by Argyroudis et al. (2019) is summarised in Table 3-3.

Table 3-3: The effects of several geo-hazards on road infrastructure (source: Argyroudis et al., 2019)

Road infrastructure affected (or biophysical vulnerability of road asset to geo-hazard)	Geo-hazards (or biophysical determinants for road biophysical vulnerability)	Examples of possible impact
(1) Embankments and cuttings (2) Pavement	Fluvial/river flood	(1) Scour, slope erosion and instability (2) Inundation, washout, deterioration, skid-resistance loss
(1) Embankments and cuttings (2) Pavements	Fluvial/surface flood	(1) Settlement, sliding/slumping (2) Inundation, washout/cracking
(1) Embankments and cuttings (2) Pavements	Landslides (incorporating sliding, debris flow, mudflow)	(1) Slope: failures along discontinuities, toppling failures and falls (2) Road may be closed due to debris flows or mudflows
(1) Pavements, embankments and cuttings	Earthquake	(1) It may cause settlement, heave or rotational/slump failure and so on
(1) Cuttings, slopes and embankments	Drought	(1) Ground stability impacts (e.g. shrinkage of clay materials)

3.3.2 Studies addressing social vulnerability

Through the relevant literature, several social vulnerability studies were summarised in the Table 3-4.

Table 3-4: The consideration for social vulnerability studies

Components of vulnerability	Component determinants			
Sensitivity	Investment		Elderly (over 65) Children (below 15)	In rural Africa, children often are withdrawn from school in order to help carrying loads for their households. This exerts negative impact on their education (Booth et al., 2000). Rufat et al., (2015) stated that low level of education may cause low level of income from a long period perspective. Ipingbemi (2010) stated that elderly in particular for elderly women in Ibadan, Nigeria, are difficult to travel to market and other service stations due to their physical constraints. Porter (2013) stated that such group

		Human assets		in Ibadan is vulnerable to insecure farming income in the context of climate change, as they have a difficulty in diversifying their income.
			Disabled	Gartrell (2010) states, in rural Cambodia, the disabled rarely has access to economic resources and employment opportunities outside the villages due to their impairment. Therefore, they have few income sources. In Fuji and Pakistan, only small proportion of disabled receives for their self-employed business due to lack of access to credit (Economic and social commission for Asia and the Pacific, 2012).
			Women Female-headed household	Access to assets, resource and several services (e.g. education, agricultural inputs) is limited to women and female-headed household in Tanzania (Osorio et al., 2014), in rural Thailand and Vietnam (Klasen et al., 2011). This leads to two groups lower income level and reinforces their poverty. Barros et al. (1994) described female-headed households in Brazil as poor, as members in such type of household lack earning power. Eriksen et al. (2005) stated that women in Mbitini in Kenya and in Saweni sub-village in Tanzania cannot collect honey or obtain skilled employment opportunities (e.g. carpentry), which are more reliable income-generating activities. In female-headed households, women have no time to undertake paid work or engage in trading, as domestic tasks (e.g. looking after children) entail a large amount of time. Accordingly, women and female-headed households in both sites have low income and lack capacity to cope with harmful events (e.g. drought). Access to assets, resources, and services (e.g. education, agricultural inputs) is limited for women and female-headed households in Tanzania (Osorio et al., 2014) and in rural Thailand and Vietnam (Klasen et al., 2011). This, in turn, leads to lower income levels and reinforces the poverty of these two groups.
		Productive assets	Pasture	Alary et al. (2011) stated that 60% of households in the Office Du Niger area of Mali are dependent on livestock income to cope with lack of food and/or urgent medical expenditure. Du-Pont et al. (2020) found that raising livestock is a substantial income source for total households in rural communities near the Great Fish River Nature Reserve in South Africa. The study's poverty analysis revealed that a high proportion of livestock income tends to reduce

				poverty. In this study, livestock production is related to grazing in the reserve.
			Arable land	Morris and Brewin (2013) stated that the arable land in Somerset, England, is flooded. Willow and arable crop are affected. This lowers relevant income, thereby weakens coping capacity.
		Collective assets	Rural roads (including all season road)	Burrow et al. (2018) affirmed that road condition impacts transport costs and travel times. Burrow (2014) stated that when a community has higher transport cost and travel time, it has less resources to spend on its assets. As a result, less assets could be mobilised to cope with the effects of a hazardous event. Iimi et al. (2016) suggest that the less all-season roads mean provision of all-season access for less population in rural area. A case study of all reason access roads in Mozambique and Uganda reveals that low density of such roads hinders social and economic activities, so that the poverty is reinforced. World Bank Group (2006) stated a significant correlation between the coverage of all-season roads and agricultural production in Kenya. Even if not causality, low coverage leads to low agricultural production, thereby low level of agricultural income. This cause income-related poverty in agricultural dominant area. Doe et al. (2020) stated that roads in the slum areas of Chinasapo in Lilongwe City, Malawi and Ayigya Zongo in Oforikrom Municipality, Ghana are limited since unauthorised building extensions occupy road construction space. As such, local settlement lacks road route from their houses to amenities. This prevents slum dwellers from going about their social and economic activities.
			Rural transport service	Porter (2013) stated that transport services in rural Sub-Sahara Africa is poor and highly charged. Alternative ways to transport goods (e.g. head-loading) take more time than transport services do. This leads to time poverty because time for productive tasks (e.g. farming) is considerably reduced. Poor and unaffordable transport services result in longer travel time to health centres. For the education sector, poor and unaffordable transport services lead to low or late enrolment, truancy, and early dropout. Braun and Aβheuer (2011) affirmed that the low level of education in Dhaka's slums in Bangladesh is a key factor leading to residents' low-income level.
	Stores	Karagiorgos et al. (2016) in their assessment of social vulnerability considered lack of financial saving as a determinant of social vulnerability. In the case study of		

		East Attica, Greece, more than 85.6% of interviewees reported having no financial saving to cope with the current socio-economic crisis in Greece. This increases social vulnerability in East Attica.
	Claims	Hahn et al. (2009) in their assessment of climate change vulnerability considered external help, such as help from relatives, as a vulnerability determinant. In the case study of Moma and Mabote Districts in Mozambique, over 90% of households do not receive any assistance from the local government to cope with the impact of climate change, and this increases their vulnerability. Braun and Aβheuer (2011) stated that residents in Dhaka's slums are willing to provide food, clothes, and money for other members so that they can cope with the crisis. Chomsri and Sherer (2013) studied the impact of the 2011 mega flood on people in Thailand. They found that affected people received little external help, and this was a major social vulnerability determinant.
Resilience	Community participation	Communities are encouraged to participate in climate-resilient roads projects in some communities in Myanmar (Asia Development Bank, 2019). Through the climate-resilient roads projects, communities could adapt to the changing climate. In other words, the original roads serving communities are non-climate resilient, hence, they are vulnerable to climate-induced geo-hazards. In order to hinder road damage, communities construct new climate resilient roads or upgrade the original roads into climate resilience for purpose of adapting to new climatic environment.

3.4 Uncertainty within vulnerability assessment

Several approaches could be used to aggregate the determinants of vulnerability, Vose (2008) and Burrow (2014) evaluate the relationship between vulnerability and its components (i.e., exposure (E), sensitivity (S), and resilience (RE)) (see Eq. 4-1) through multiplicative formula (i.e., $V = \mathrm{E} \times \mathrm{S} \times \mathrm{RE}$, Eq. 3-2), while Preston et al. (2008) suggests an additive formula (i.e., $V = \mathrm{E} + \mathrm{S} + \mathrm{RE}$, Eq. 3-3). In addition to this, Gornitz (1991) propose the vulnerability aggregation via the square root of the geometric mean (i.e., $V = \sqrt{\frac{\mathrm{E} \times \mathrm{S} \times \mathrm{RE}}{3}}$, Eq. 3-4), while Cogswell et al. (2018) suggest the true geometric mean (GM) method (i.e., $V = \sqrt[3]{\mathrm{E} \times \mathrm{S} \times \mathrm{RE}}$, Eq. 3-5).

In order to deal with this aggregation uncertainty, a logic-related approach was identified, as it is relatively easy and understandable, to approximately model the relationship between vulnerability and its three components (such as if exposure is high AND sensitivity is high AND resilience is low, THEN vulnerability is high). Based on this logical relation, the inputs of exposure, sensitivity and resilience infer the output of vulnerability. This example could be viewed as a rule consisting of antecedent (AND) and consequent (THEN) parts.

There are two kinds of logics, namely, classical logic and uncertainty logic, which is elaborated below.

3.4.1 Classical logic

In the classical logic, a proposition that is a single statement is referred to as a simple proposition, such as "this laptop is good" (Ross, 2005). It is worth noting that this proposition consists of an individual object (this laptop) and predicate to describe the object (is good); hence, it is also referred to as a predicate proposition (Lee, 2005). Besides, the proposition has a basic notation that is either absolutely confirmed (true) or is absolutely not confirmed (false) (Allendoerfer and Oakley, 1955). Therefore, a classical-logic-based inference process fails to operate if the truth value of exposure, sensitivity and resilience propositions is uncertain. This is the case if the truth value of proposition is neither absolutely true nor absolutely false. The inference is a logical form that takes an antecedent and returns a consequent via a rule using an implication operator (symbolised as →), i.e., this operator can imply proposition q by proposition p. As suggested by Lee (2005), modus ponens (MP) is an inference process as follows:

Fact (p): x is a

Rule ($p \rightarrow q$): if x is a, then y is b

Result: y is b.

3.4.2 Uncertainty logic

Uncertainty logic handles uncertain propositions (Núñez et al., 2013). Briefly, uncertainty logic not only expresses the uncertainty of a proposition but also propagates uncertainty between propositions via the logical operations. Through the relevant literature review, there are two types of uncertainty logics, i.e., fuzzy logic and probabilistic logic. Fuzzy logic can express uncertainty involved in the propositions via membership function (see Chapter 2) (Zadeh, 1965). Probabilistic logic expresses the uncertainty of the propositions by means of a probability value (Webber and Nilsson, 1981).

3.4.2.1 Fuzzy logic

3.4.2.1.1 Fuzzy logical operations

As stated in Chapter 2, membership function can model fuzzy and vague uncertainties related to linguistic description. Therefore, fuzzy logic expresses uncertainty in a proposition using membership function to quantify linguistic variables in the proposition (such as exposure is very high, "very high" is a linguistic variable (see Appendix A). Consequently, fuzzy logic is a form of many-value logic where any proposition may take a real number in [0,1] as the truth value. Here, 1 represents a proposition that is absolutely true, whereas 0 indicates a proposition that is absolutely false. However, some propositions are neither completely confirmed nor completely disconfirmed. For such circumstances, fuzzy logic can assign a number between 0 and 1 as the truth value of the proposition. The truth value is considered to be degree of belief in the proposition.

For example, the word "approximately" could be quantified as $\pm$ 0.1, thereby "approximately two tonnes" is regarded as the fuzzy set (1.9,2,2.1) presumably characterised by a triangular membership function in Figure 3-6. This fuzzy set can be also seen as a fuzzy number that can be used to represent the uncertain parameter estimation (see Section 4.3 in Chapter 4). In a predicate proposition, an individual object could be represented by a variable; for example, the weight of a whale is a variable. If the variable takes an element in the set, the membership grade of the element in the set is the truth value of the proposition. Therefore, when the actual weight of the whale is 1.95 tonnes, the truth value of the proposition "the whale is approximately 2 tonnes" is 0.5 (see Figure 3-6).

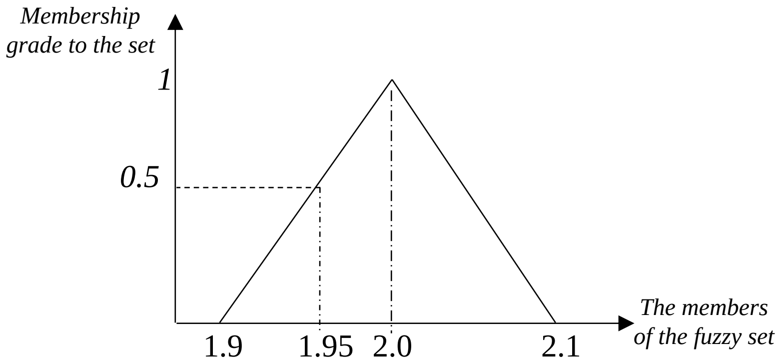


Figure 3-6: Triangular membership function for fuzzy set (1.9,2,2.1)

In fuzzy logic, inference process described in section 3.4.1 is based on fuzzy rule, i.e., rule contains uncertain linguistic descriptor (e.g. very high) characterised by membership function. Such fuzzy rule typically consists of more than two simple propositions (also named as compound proposition) combined by logical connectives such as AND, THEN corresponding to logical operators as conjunction and implication.

3.4.2.1.2 Fuzzy system

A major application of fuzzy logic is the fuzzy system. The classical fuzzy system utilises fuzzy rule(s) to express a logical relationship, such as a relationship amongst states (or values) of linguistic variables (Klir, 2006). The states of the variables in a fuzzy system are linguistic terms (e.g., very high, high, medium, low, very low) characterised by fuzzy sets. Based on this, the fuzzy system is considered to be a universal approximator to an algebraic function via an implicative relation between antecedent (corresponding to independent variable in a function) and consequent (corresponding to dependent variable in that function) (Kosko, 1994; Ross, 2005). Therefore, it could address the uncertainty with respect to mathematical vulnerability aggregation.

As described by Klir (2006), there are two types of fuzzy systems, namely, knowledge-based and model-based. In knowledge-based fuzzy systems, relationships between variables are described via fuzzy rules expressing the knowledge of domain experts, often by natural language. Model-based fuzzy systems are simultaneously based on conventional system modelling and relevant fuzzy mathematics and thereby approximate classical mathematical system.

In both kinds of fuzzy systems, a fuzzy rule base is a pivotal component. Obviously, a fuzzy rule base is a collection of fuzzy rules and has several advantages as follows (Durkin, 1994):

- Natural expression: each rule can be expressed by natural language, so that they are understandable.

- Utilisation of uncertain knowledge: each rule expresses an uncertain relation between vulnerability and its components (i.e., uncertain knowledge with respect to this relation).
- Modularity of knowledge: each rule represents an independently chunk of knowledge regarding the relationship between vulnerability and its components, thereby it is straightforward to review and verify the correctness of the rule.
- Ease of expansion or reduction: the new rule can be added or/and the extent rule can be deleted in the rule base only if the addition or/and deletion is verified. This is because the rule base is separate from the inference system described in section 6.5, i.e., knowledge concerning vulnerability is separate from the reasoning associated with the knowledge.
- Tolerance of partial matching: it is not necessary to completely match the antecedent of the rule during reasoning with that rule.

3.4.2.1.3 Application of fuzzy logic within vulnerability assessment in road industry

Through the relevant literature review, the utilisation of fuzzy logic within vulnerability assessment in road industry mainly focus on biophysical vulnerability. For example, Pan (2005) uses fuzzy logic to deal with the biophysical vulnerability of highway construction, i.e., the impact of rainfall on productivity (i.e., productivity loss referring to such as the delayed progress of embankment construction task) and duration of highway construction activities. The fuzzy rule used in this study has, for example, "IF embankment exposure level to rain is very large and drench frequency is large, THEN adverse consequence on productivity is very large." Drench refers to a certain level of rainfall numerically expressed by daily precipitation between 20 mm and 50 mm.

Jeong et al. (2017) and Wang et al. (2019) also employ the fuzzy logic to analyse the impact of climate on road assets. Through such analysis, Jeong predicts the road service life, while Wang et al. propose the relevant adaptation strategy to cope with such impacts.

3.4.2.2 Probabilistic logic

Through the relevant literature, two approaches related to probabilistic logic are identified, i.e., certainty factor (CF) approach and Bayesian theorem. The certainty factor and Bayesian theorem based probabilistic logic follows an inference process, i.e., the prior probability of an event is updated based on received new information regarding the event. Prior probability refers to the probability of an event based on the existing knowledge before new information is collected, while the updated priori probability of the event due to the acquisition of new information is termed as posterior probability. Therefore, the certainty factor approach and Bayesian theorem are described in sections 3.4.2.2.1 and 3.4.2.2.2.

3.4.2.2.1 Certainty factor approach

According to Shortliffe and Buchanan (1975), the certainty factor approach (CF) is based on the difference between measures of belief (MB) and disbelief (MD). For example, the belief degree for H favoured by E can be calculated as follows:

$$\text{CF}\ (H,E) = \text{MB}\ (H,E) - \text{MD}\ (H,E) \qquad Eq. 3-6$$

Where E is an evidence and H is a hypothesis in a rule showing H (corresponding to a proposition, q, in section 3.4.2.1) implied by E (corresponding to a proposition, p, in section 3.4.2.1). MB (H,E) refers to the change in belief degree for H in the presence of E, whereas MD (H,E) refers to the change in disbelief degree for H in the presence of E. It is worth noting that E is unable to change in disbelief degrees for H, if E changes in belief degrees for

H. Furthermore, MB $(H, E) >$ MD (H, E) means that E supports H, whereas MB $(H, E) <$ MD (H, E) E supports the negation of H.

Through the literature review, a major utilisation of the certainty factor approach has been in the development of MYCIN, an artificial intelligence program for disease diagnosis. A brief description of MYCIN can be found in Appendix B.

3.4.2.2.2 Bayesian theorem

Bayesian theorem refers to the calculation of the conditional probability of each possible causes for a given outcome (Pate'-Cornell, 1996). The formula for such calculation is as follows:

$$\mathrm{P(A|B)} = \frac{P\ (B|A)\ \times\ P(A)}{P(B)} \qquad Eq. 3-7$$

Where $\mathrm{P(A|B)}$ is the probability of the event A based on the event B occurring. $P(A)$ is the probability of the event A occurring, $P(B)$ is the probability of the event B occurring. $P\ (B|A)$ is the probability of the event B based on the event A. $P\ (B|A)\ \times\ P(A)$ is the probability of both events A and B occurring.

Through the relevant literature review, one of the Bayesian theorem utilisations is for the development of PROSPECTOR (a computer-based consultant system for mineral exploration) and its brief description can be found in Appendix C.

The Bayesian theorem is utilised within Bayesian network model, including two elements (i.e. node and edge) (Bensi et al., 2011). Nodes represent variables, while edges refer to the conditional dependency between variables. For example, the water level of a stream (i.e. variable A as node A) is dependent on the amount of precipitation (i.e. variable B as node B);

therefore, the dependence between variables A and B can be linked via an edge. In the Bayesian network model with two variables, where one is conditionally dependent on another (or two nodes are graphically linked via an edge), the state of one variable can be updated when the state of the other is given.

Bensi et al. (2011) has shown that the Bayesian network model can be used for road network vulnerability assessment because it can capture infrastructure risk (e.g. road risk) and take into account the influence of hazards on the infrastructure. It thus offers a risk-informed decision-making tool (Chen et al., 2019). Moreover, it can integrate different forms of dependent and interdependent infrastructures (Haraguchi and Kim, 2016). For example, the Bayesian network model can be used to express the propagation of failure within an infrastructure system. Dong et al. (2020) employed the Bayesian network model to establish a probabilistic model where the failure (e.g. inundation) of a road network is inferred in a probabilistic manner by considering the road and drainage channel network topology, hydrological elements (e.g. rainfall, stream) and their relationship with inundation states. Notably, the probabilistic model developed is a risk-hazard model (see Section 3.2.2.1).

3.4.2.3 Comparison of classical logic, fuzzy logic and probabilistic logic

Classical logic has a major shortcoming, i.e., its low level of generality. The low level of generality reflects that the proposition considers only two truth values: true and false. Additionally, classical logic cannot numerically characterise the predicate of a predicate proposition so that it fails to address uncertainty.

The certainty factor approach- and Bayesian theorem-based probabilistic logic fails to deal with fuzzy predicate (i.e. the predicate of a predicate proposition contains something not sharp, unclear or not specific). For example, Zadeh (1983) provided the following proposition: John has a duodenal ulcer (CF = 0.3). He stated that having a duodenal ulcer is a matter of grade, such as a mild or severe ulcer. Therefore, “having duodenal ulcer” is a fuzzy predicate, which renders the proposition a fuzzy proposition. The CF of 0.3 means that John is believed to have a duodenal ulcer with 30% certainty, whatever the degree (severity) of the ulcer. Ideally, it is preferable to know the probability of a certain severity of duodenal ulcer he has; that is, the probability of a fuzzy event. Fuzzy logic can deal with such probability, although it is beyond the scope of this chapter. (For detail, see Zadeh, 1968). Hence, fuzzy logic can handle not only fuzzy-related uncertainty but also probability-related uncertainty (Zadeh, 1983). In this regard, fuzzy logic is more powerful than probabilistic logic.

Additionally, such probabilistic logics need to comply with independence (see Appendices B and C). Therefore, exposure, sensitivity and resilience are assumed to be mutually independent if probabilistic logic is used to infer vulnerability. For example, the occurrence of exposure does not affect the occurrence of sensitivity; that is, $P(sensitivity|exposure) = P(sensitivity)$. However, initial impact resulting from exposure could cause further impact due to sensitivity. Hence, exposure leads to sensitivity; that is, $P(sensitivity|exposure) > P(sensitivity)$. To closely resemble reality, it is best not to make unnecessary assumptions, such as the independence of exposure, sensitivity and resilience. Hence, probabilistic logic is not suited for the vulnerability issue at hand.

Exposure, sensitivity, resilience and vulnerability are consequently all matters of degree (such as “extremely low”, “low” and so on). They are not mutually independent. Hence, fuzzy logic is more appropriate than classical and probabilistic logics for addressing vulnerability aggregation uncertainty.

3.5 Gaps in current knowledge between road investment prioritisation and rural community road access vulnerability

Through the review of the literature on the road investment prioritisation summarised in Chapter 2, it was found that (a.) CBA and MCA are best suited to the evaluation of the road programme itself, and (b.) the focus of the identified road asset management system (e.g. APMS described in Section 2.2.2.1) is on the current pavement condition evaluation and its future condition predication so as to determine the relevant road investments. Both are not adept at considering the likelihood of stressors nor the coping and adaptive mechanisms of the affected system (e.g., a rural community). Therefore, the target of their application is not on the impact of undesirable road condition and loss of road access provision as stated in Chapter 1.

Vulnerability assessment described in this Chapter however provides a means of dealing with the issue with respect to the likelihood and impact of reduced access due to a variety of hazards. The evaluated impacts resulting from diverse disruptions of road links can be used to be a basis for prioritising road investments.

The review of vulnerability approaches/models described in section 3.2 has shown that EV models are preferable to R-H models when determining rural community vulnerability to lack of access as required in this research. Since the focus of R-H models is only on the environmental system rather than coupled human and environmental system, they do not take into account the sensitivity and resilience following the exposure to perturbation or/and stress/stressor.

Consequently, for this research it was decided to build an EV model to assess the vulnerability of rural communities to likely loss of access caused by geo-hazards.

3.6 Summary

This chapter described vulnerability assessment in terms of its related concepts, vulnerability examples and models, and uncertainty. For the relevant concepts, the definitions of vulnerability, vulnerability determinants and risk and vulnerability assessment were described. Following this, seven vulnerability examples and four vulnerability models were identified. Each of examples/models has their own perspective on vulnerability. For example, EV models provide the most comprehensive treatment vulnerability compared with the others (such as Burrow (2014) use EV model to assess rural community vulnerability to the loss of rural road access provision).

Consequently, an aggregation uncertainty involved in EV-models-based vulnerability assessment was identified. A logical approach was identified to be an appropriate approach to handle this uncertainty. Furthermore, the fuzzy logic was identified to be the most appropriate to deal with such uncertainty compared with classical and probabilistic logics.

Accordingly, a research gap was identified as no study use an EV-model-based vulnerability approach in conjunction with the use of fuzzy logic for road investment prioritisation. Based on such research gap described in Section 3.5, next Chapter will develop a methodology.

CHAPTER 4 METHODLOGY

The literature review in Chapters 2 and 3 illustrated that there is a need for research to improve existing methods of prioritising rural road investment. Chapter 3 suggested that a new vulnerability-based approach could be a viable means of overcoming the shortcomings of existing approaches described in Chapter 2 as it could be used to consider socio-economic factors related to undesirable rural road conditions and the disruption of rural road access provision. Additionally, Chapters 2 and 3 highlighted the need for an approach that can address (a.) the lack of data and data uncertainty, and (b.) the uncertain aggregation of vulnerability components (i.e., exposure, sensitivity and resilience) (see Chapter 5).

Consequently, the aim of this research is to develop an uncertainty-based approach for the assessment of rural community vulnerability to a lack of access provision. The methodology, undertaken to develop this approach and its theoretical framework, is described in this chapter as follows:

1. Research methodology (Section 4.1): the methods used to carry out the research.
2. Theoretical framework (Section 4.2): the structure of the vulnerability assessment model.
3. Dealing with uncertainty (Section 4.3): how uncertainty associated with expert judgement and vulnerability's aggregation uncertainty has been taken into account.
4. Data collection (Section 4.4): the approach used to collect data.

The aims of this research has been achieved through a vulnerability assessment model. Using the model, the vulnerabilities of communities can be assessed, and the results can be used as a basis for road investment prioritisation. To improve the validity and accuracy of the model, the methodology adopted in this study considers uncertainties. For example, parameter uncertainty allows the numerical value of a parameter to be expressed as a range (e.g. from 10 to 20) rather than an exact number. This methodology also assumes that vulnerability = [0,1] to quantify the acceptable limit of vulnerability (e.g. low, medium and high; See Burrow, 2014). This is explained in more detail in Section 4.2.3.

4.1 Research methodology

The research methodology is summarised in Figure 4-1 and described below.

1. Review of the literature: A literature review was carried and is described in Chapters 2 and 3 to investigate (a.) existing prioritisation approaches/techniques for road investments and their limitations, (b.) vulnerability-based approaches and (c.) theories and techniques for addressing uncertainty. This achieves research objective 1 in Chapter 1.3.
2. The identification of relevant modelling and uncertainty-solving approaches/techniques. The most appropriate techniques identified can assist with (a.) developing a theoretical framework for a vulnerability assessment model described in Section 4.2, which achieves objective 2 and, (b.) dealing with uncertainty involved in the vulnerability model, which achieves objective 3.
3. The identification of relevant data collection methods: The most appropriate method is identified to collect data used to demonstrate the model.
4. The demonstration of the applicability of the model via a case study. The case study is given in more detail in Chapter 7 (this achieves objective 4).

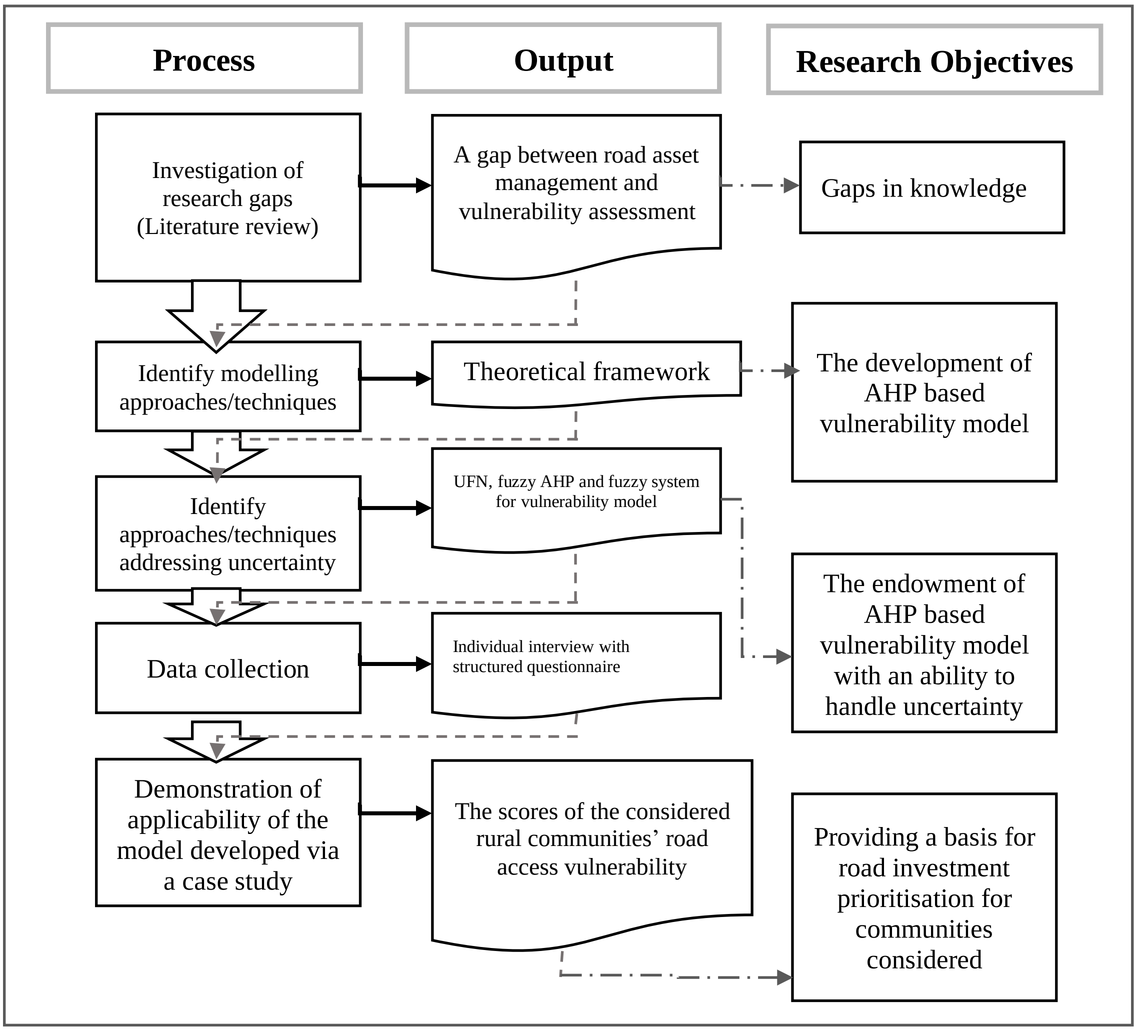


Figure 4-1: Research methodology

4.2 Theoretical framework

4.2.1 Development of MCA based vulnerability assessment model

Based on the needs of the developed approach to provide useful information to decision makers so that road investments for rural communities can be prioritised, it was felt that the developed approach should have the following features:

(a) Enable a number of different criteria, with different units of measurement, to be combined and used to determine the vulnerability of rural communities

(b) Be able to consider the relative importance of these criteria

(c) Take into account potentially complex information which may also be uncertain

(d) Enable the use of expert judgement so as to support the inclusion of structure, openness, experience and knowledge during the decision-making process

(e) Be transparent and easily understood by decision makers.

As the proposed approach seeks to combine large amounts of complex information and conflicting evaluation criteria it was decided to use an MCA framework, as recommended by the British standard for risk management, BS EN 31010:2010 (BSI, 2010). Furthermore, as described in Chapter 2, MCA is able to take into account factors within the model which are either monetised or non-monetised (criterion (a) above), deal with the relative importance of these factors (criterion (b)) and uncertain information (criterion (c)), allow for the use of expert judgment (criterion (d)), and provide a rational and transparent basis for decision making (criterion (e)) (DCLG, 2009; Moran et al., 2017).

4.2.2 Technique selection

From the literature three potential MCA techniques were identified for further consideration, namely the Multi-Attribute Utility Theory (MAUT), the Outranking Method (OM) and the Analytic Hierarchy Process (AHP) (see Section 2.2.1.2 in Chapter 2) (DCLG, 2009; Moran et al., 2017). For the task in hand all three techniques have advantages and disadvantages and therefore the following criteria, based on those recommended by DCLG (2009), were used to identify the most appropriate technique for the task:

1. Internal consistency and logical soundness.
2. Transparency.
3. Ease of use.
4. Data requirements.
5. Resource requirements for the analysis process.
6. Ability to provide an audit trail.
7. Software availability.

All three methods may be considered to be consistent and logically sound (criterion (1)), require similar data that is assessed against a set of indicators (4), have similar data collection and processing needs (5) and are not difficult to programme (7).

MAUT requires the assignment of a numerical value to each of alternatives considered (DCLG, 2009). In its simplest form, this numerical value is the weighted sum of the performance measures given by each criterion measured against the alternative. This makes MAUT transparent (Ortiz-Garcia et al., 2005). However, the requirement of MAUT for the definition of marginal utility functions for each criterion is not a trivial task and is therefore problematic to use when a large number of criteria need to be considered (Ortiz-Garcia et al., 2005; Moran et al., 2017).

The OM refers to the concept of a project alternative dominated by another (DCLG, 2009). Weighting factors can be utilised to make some indicators of value more of a contribution to the score attributable to a project than others. Although OM advocates interaction between decision makers, it is overly dependent upon defined concept of outranking and on ways to set and modify the outperformance thresholds (Moran et al., 2017). As a result, OM was considered to be less transparent (criteria (2)) and provide less of a clear audit trail (criteria (6)) for non-specialist users (Ortiz-Garcia et al., 2005; Moran et al., 2017).

In contrast to the MAUT and OM techniques, for the problem considered AHP allows the relative significance of the weighting factors to be easily determined using expert judgement (criteria (2) and (3)) and it can be considered to be straightforward and transparent. This will allow it to be easily adopted by senior decision makers and acceptable to all stakeholders. As a result, the AHP methodology was selected for the task in hand.

4.2.3 Development of AHP based vulnerability assessment model

Using the AHP methodology described in Section 2.2.1.2 in Chapter 2 considering the three components of vulnerability, a model of assessment of vulnerability was developed. The model consists of vulnerability identification, analysis and evaluation described in Chapters 5 and 6. As suggested by Burrow (2014), a rural community road access vulnerability is expected to (a.) increase with the increment of exposure (E) and sensitivity (S), (b.) decrease with higher resilience (RE). Therefore, the relationship between exposure, sensitivity and resilience, and vulnerability was represented in Eq. 4-1 (this equation is not intended as a mathematical function), adapted from Nguyen et al. (2019). In order to facilitate the quantification of acceptable limits of the vulnerability index, this research assumes $E, S, RE = [0,1]$, 0 representing very low exposure and sensitivity, resilience, 1 very high exposure, sensitivity and resilience.

$$V = \frac{E \times S}{RE} \qquad Eq. 4-1$$

To gain further insight into the three components of vulnerability in Eq. 4-1, a vulnerability tree was developed by breaking vulnerability components into vulnerability determinants. Figure 4-2 shows the vulnerability tree that has been broken at the vulnerability component and vulnerability determinant levels as follows: (a) risk events of Ri_1, Ri_2,…, Ri_i at vulnerability determinant level affect the level of E at vulnerability component level; (b) sensitivity determinants of DS_1, DS_2,…, DS_i at vulnerability determinant level affect the level of S at vulnerability component level; and (c) resilience determinants of DRE_1, DRE_2,…, DRE_i at vulnerability determinant level affect the level of RE at vulnerability component level.

Regarding the measurement of vulnerability components, since the literature discussed in Section 3.3.1 revealed that geohazards are a major factor threatening road assets and corresponding road access provision, they were considered to be a cause of exposure in this research. Accordingly, exposure is measured using equation 4-2 in accordance with the British standard for risk management, BS EN 31010:2010 (BSI, 2010).

$$E = W_E \times \sum_{i=1}^{n} W_{Ri_i} \times Ri_i \qquad Eq. 4-2$$

where Ri_i is the i_{th} risk event related to the probability and impact of geo-hazards on rural roads serving a community, W_{Ri_i} is the relative weight of Ri_i and $\sum_{i=1}^{n} W_{Ri_i} = 1$. It is assumed that the community considered only has one road leading to outside of the community. W_E is the relative weight of exposure compared with sensitivity and resilience.

$$Ri_i = P_i \times I_i \qquad Eq. 4-3$$

where P_i is the probability of the occurrence of i_{th} risk event, I_i is the impact of i_{th} risk event.

As suggested by Rufat et al. (2015), the sensitivity and resilience are measured as follows:

$$S = W_S \times \sum_{i=1}^{n} W_{DS_i} \times DS_i \qquad Eq. 4-4$$

where DS_i is i^{th} determinant of sensitivity and W_{DS_i}, is the relative importance, or weight, of the i^{th} determinant, and $\sum_{i=1}^{n} W_{DS_i} = 1$. The determinants used to represent sensitivity are described in Section 5.2.2. W_S is the relative weight of sensitivity.

$$RE = W_{RE} \times \sum_{i=1}^{n} W_{DRE_i} \times DRE_i \qquad Eq. 4-5$$

where DRE_i is i^{th} determinant of resilience and W_{DRE_i}, is the relative importance, or weight, of the i^{th} determinant, and $\sum_{i=1}^{n} W_{DRE_i} = 1$. The determinants used to represent resilience are described in Section 5.2.3. W_{RE} is the relative weight of resilience and $W_E + W_S + W_{RE} = 1$.

The process to identify the determinants of exposure, sensitivity and resilience is described below, whilst the determinants themselves are given in Section 5.2 in Chapter 5.

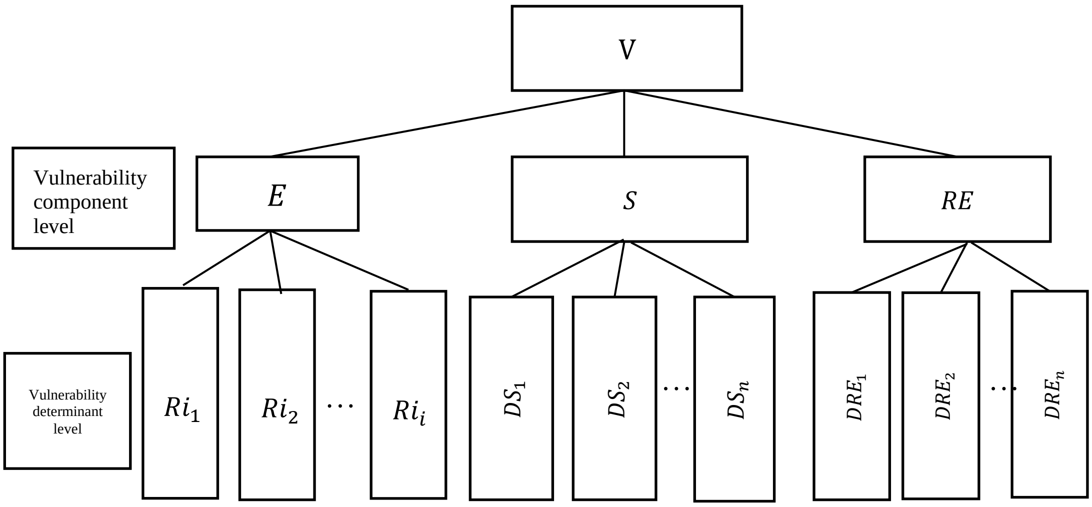


Figure 4-2: The vulnerability tree

4.2.3.1 Determinants of exposure, sensitivity and resilience

As stated in Chapter 2, risk assessment is analogous to vulnerability assessment, and the identification of a rural community road access vulnerability is a process of finding and recognising the determinants of such vulnerability. The BS EN 31010:2010 (BSI, 2010) suggests three methods to identify risks. These have been used herein to identify the vulnerability determinants and are as follows:

a) Evidence-based methods: such as reviews of historical data and check lists;
b) Systematic team approaches: where a group of experts use a systematic process to identify determinants of vulnerability via a way of a structured series of questions;
c) Inductive reasoning methods: refer to generally generalisation of any observation, such as a Hazard and Operability study (HAZOP).

Methods (a) and (b) were used herein to avoid subjectivity that may occur by adopting only one of the methods and but also to achieve adequate validity and reliability. Accordingly, the determinants associated with exposure, sensitivity and resilience were determined using the approach (a) and are described further in Chapter 5, while the validation of the identified determinants using approach (b) is described in Chapter 7. For the identification of the determinants related to (1) exposure (i.e., risk events associated with undesirable road condition risk and road access loss risk), (2) sensitivity (i.e., investment aggregated into human assets, productive assets and collective assets, stores and claims) and (3) resilience (i.e., coping capacity represented by community participation) in Chapter 5, method (c) was employed. For example, it was recognised, by reviewing the literature, that rural roads facilitate socio-economic activity for a local community (Hine et al., 2015). Therefore, risk events resulting from the impassability of rural roads due to geo-hazards were considered to be the determinants of exposure in the research (see Section 5.2. in Chapter 5). Additionally, poor rural road condition can result in relatively high transport cost and more travel time (Burrow et al., 2018) so that this could have negative impact on coping capacity for addressing hazardous event due to lack of saving or insurance in the place where the income level is low (Willroth et al., 2011). Therefore, the rural road condition could be a sensitivity contributor, as the worse the road condition, the worse the coping capacity, then the more sensitive the community is. Consequently, the value of rural road route from the community to amenities (e.g. school) considered in collective assets is identified to be a sensitivity determinant.

4.2.3.2 Component/determinant weights

The relative importance, or weight, of the exposure, sensitivity and resilience components/determinants of the models in Eq. 4-1 and the weights of their own determinants were determined using the pairwise comparison process suggested by Saaty (1980).

To achieve this, four comparison matrices associated with exposure, M_E, sensitivity, M_S, resilience, M_{RE}, and vulnerability M_V were established. The elements of the matrices were determined by comparing the determinants of each of the four measures, one against the other using the scoring system and linguistic variables given in Table 4-1. An example of a resulting comparison matrix is given in Figure 4-3. For the case study a group of experts was used for this process as described in Chapter 7.

Secondly, the resulting M_E, M_S, M_{RE} and M_V matrices were transformed into a normalised pairwise comparison matrix $\bar{M}_E$, $\bar{M}_S$, $\bar{M}_{RE}$ and $\bar{M}_V$ using Eq. 4-6.

$$\bar{a}_{ij} = \frac{a_{ij}}{\sum_{l=1}^{m} a_{lj}} \qquad Eq. 4-6$$

where a_{ij} denotes the entry in the ith row and the jth column in the M_E, M_S, M_R and M_V, $\sum_{l=1}^{m} a_{lj}$ is the sum of m of a_{ij} on jth column, and $\bar{a}_{ij}$ is the normalised entry in the ith row and the jth column in the $\bar{M}_E$, $\bar{M}_S$, $\bar{M}_{RE}$ and $\bar{M}_V$.

Finally, the weight of each of the determinants of exposure, w_E, sensitivity, w_S, resilience, w_R, and vulnerability, w_V, were established by averaging the entries on each row of $\bar{M}_E$, $\bar{M}_S$, $\bar{M}_{RE}$ and $\bar{M}_V$ via Eq. 4-7.

$$w_i = \frac{\sum_{l=1}^{m} \bar{a}_{il}}{m} \qquad Eq. 4-7$$

where $\sum_{l=1}^{m} \bar{a}_{il}$ is the sum of m $\bar{a}_{il}$ on ith row, m is the number of column in $\bar{M}_E$, $\bar{M}_S$, $\bar{M}_{RE}$ and $\bar{M}_V$.

Table 4-1: Preference index (Saaty, 1980)

Index	How important is one determinant relative to another	Preference index assigned
1	Equal importance	1
2	Moderately more importance	3
3	Strongly more importance	5
4	Very strongly more importance	7
5	Overwhelmingly more importance	9
6	Moderately less importance	1/3
7	Strongly less importance	1/5
8	Very strongly less importance	1/7
9	Overwhelmingly less importance	1/9

$$
\begin{array}{cc} & \begin{array}{cccc} j_1 & j_2 & \cdots & j_n \end{array} \\
A = \begin{array}{c} i_1 \\ i_2 \\ \vdots \\ i_n \end{array} & \begin{bmatrix} 1 & 3 & \dots & \frac{1}{5} \\ 7 & 1 & \dots & 7 \\ \vdots & \vdots & \vdots & \vdots \\ \frac{1}{5} & \frac{1}{7} & \dots & 1 \end{bmatrix} \end{array}
$$

Figure 4-3: Comparison matrix

4.3 Uncertainty

4.3.1 Types of uncertainty

For the AHP based vulnerability assessment model developed above, three kinds of uncertainties were recognised. The first concerns judgement uncertainty (see Section 2.3 in Chapter 2). For example, an analyst may have to make an uncertain judgement (or judgement with low or no confidence) when estimating or predicting the value of parameters in a mathematical model due to lack of relevant knowledge and information (Bedford and Cooke, 2001). In order to eliminate the uncertainty in judgement, it is preferable to give an uncertain value of the parameter (i.e., parameter uncertainty) instead of a precise one so as to enhance the confidence of the judgement.

The second is uncertainty related to the pairwise comparison process (see Section 2.3 in Chapter 2). As stated in Section 4.2, a preference index (see Table 4-2) can be used to guide participants in making judgements of the relative importance of a component/determinant. However, participants may find it difficult to convert their subjective opinions into an exact number (Van Laarhoven and Pedrycz, 1983; Buckley, 1985; Mikhailov, 2004). For example, a participant may feel that they cannot give a crisp number, when making a judgement of the relative importance of two determinants (such as "1" indicates "*'A'* is equally important to *'B'*").

The third is to do with aggregation uncertainty, i.e., the uncertainty to mathematically aggregate the exposure, sensitivity and resilience into the vulnerability (see Section 3.4 in Chapter 3).

In order to deal with these uncertainties, the fuzzy concept related approaches were used. First, the uncertainty of expert judgement on the parameter's value was addressed using linguistic expression (such as the weight of the whale is between 2 and 2.5 tonnes) represented by UFN described below. Second, the fuzzy AHP approach was used to model uncertainties associated with the pairwise comparison, and third, a fuzzy system was used to deal with the aggregation uncertainty of vulnerability.

4.3.2 Uniform format number (UFN)

As suggested by Bojadziev and Bojadziev (2007), fuzzy number could represent the linguistic express (e.g. (27, 28, 29, 30) represents “close to 28.5”), thereby, the linguistic expression of parameters’ value can be transformed into fuzzy number. Although there were several types of fuzzy number (such as triangular, trapezoidal and Gaussian (or bell shape) fuzzy numbers), trapezoidal fuzzy number was utilised as it is found by Barua et al. (2014) to have the practical success by theoretical interpretation when compared to other fuzzy numbers. Consequently, a uniform format number (UFN) index, based on trapezoidal fuzzy number, was used and is described in Chapter 7.

4.3.3 Fuzzy AHP approach

The fuzzy AHP approach was used to determine the relative importance (weights) of the three components in Eq. 4-1 and their own determinants (Eq. 4-2, Eq.4-4 and Eq. 4-5). Using this approach, participants are provided with a range of numbers (i.e. fuzzy numbers, e.g., (2,3,3,4) instead of 3). The approach provides participants with a more flexible way to express their judgements in either linguistic terms or corresponding number ranges when determining the relevant importance of the weights (Cheng et al., 1999; Bozdag, 2003; Wu et al., 2004; Kahraman, 2004).

From the literature, several specific fuzzy AHP approaches were identified. A comparison of their main characteristics, strengths and weaknesses are summarised in Table 4-2. Following an analysis of these approaches it was decided to adopt that suggested by Buckley (1985) since it advocates the use of trapezoidal fuzzy numbers (or trapezoidal membership function) which have the practical success by theoretical interpretation as described above.

Table 4-2: The comparison of various fuzzy AHP approaches (Source: Gulcin Buyukozkan et al., 2007)

References	The main characteristics of the approach	Strengths (S) and weaknesses (W)
Van Laarhoven and Pedrycz (1983)	• Replace crisp number representing preference terms (such as equal importance) with triangular fuzzy numbers • Utilise Lootsma's logarithmic least square method to obtain fuzzy weights and fuzzy performance values	(S) Reciprocal matrix can encompass the modelling of opinions of several decision makers (W) The linear equations do not always have a solution (W) It requires significant computational effort, even for a small problem (W) Only triangular fuzzy numbers can be used
Buckley (1985)	• Replace crisp number with trapezoidal numbers • The geometric mean method is used to derive fuzzy weights and performance values	(S) It is easy to extend to the fuzzy case (S) It guarantees a unique solution to the reciprocal comparison matrix (W) It requires tremendous computation
Boender et al., (1989)	• Revises van Laarhoven and Pedrycz's approach • Design a more robust method to normalise the local prioritise	(S) It can model the opinions of various decision makers (W) It requires tremendous computation
Chang (1996)	• Synthetical degree values • Layer simple sequencing • Composite total sequencing	(S) It requires relatively low of computation (S) It follows the procedure in Saaty's AHP and does not have extra operations (W) Only triangular fuzzy numbers can be used

Cheng (1997)	• Establishes fuzzy standards • Taking advantage of the concept of entropy to calculate aggregate weights • Represents performance values by membership functions	(S) The computational requirement is not tremendous (W) It is based on probability and possibility measures, as probability is known if entropy is utilised

4.3.4 Fuzzy system

Through the review of the literature, three inference methods used in fuzzy systems were identified as being potentially appropriate to design a fuzzy system for vulnerability modelling. These are the Mamdani method, the TSK method and the Tsukamoto method and are described below.

4.3.4.1 Mamdani method

In a fuzzy system using the Mamdani method, rules typically derive from domain experts' experience and knowledge (Ross, 2005). Hence, the Mamdani fuzzy system is knowledge-based. For the implication of premises and consequent by a rule, the Mamdani method employs the minimum operator to mathematically express such implication (see Section 3.4.2.1 in Chapter 3) (Mamdani and Assilian, 1975). Furthermore, when more than one rule in the Mamdani based fuzzy system are employed, the maximum operator is used to aggregate the rules. As a result, the Mamdani fuzzy system needs a defuzzification strategy referring to the transformation of fuzzy result deriving from the aggregated rules into an exact number (see more details in Section 6.5.3.3 in Chapter 6).

4.3.4.2 TSK method

In a fuzzy system using the TSK (Takagi, Sugeno, and Kang) method (sometimes referred to as the Sugeno method, or the TSK fuzzy system), the rules are produced from a given input and output data set (Ross, 2005). In other words, the consequent in a TSK based rule is characterised by a function (Takagi and Sugeno, 1985; Sugeno and Kang, 1988). Therefore, such a system is considered to be model based. For instance, a rule in the TSK fuzzy system, which has three inputs $w \in W$, $x \in X$ and $y \in Y$, and an output z, has the following form:

If exposure is W and sensitivity is X and resilience is Y, then Z is $Z = f\ (W, X, Y)$

Where $Z = f\ (W, X, Y)$ is a polynomial function in the inputs w, x and y.

Since the rules in a TSK based fuzzy system generate crisp outputs given by the function mentioned above, this kind of fuzzy system does not need to carry out defuzzification.

4.3.4.3 Tsukamoto method

In the fuzzy system using the Tsukamoto method, the consequent of the rule is represented by a fuzzy set characterised by a monotonic membership function (Tsukamoto, 1979). Since this kind of membership function is difficult to obtain through human expert, rules in a Tsukamoto fuzzy system cannot be acquired via expert knowledge, thereby it is not a knowledge-based system (Czabanski et al., 2017).

By a monotonic membership function, the membership values generated by the premises clause of a rule induce the output of that rule which is a crisp value. In other words, each of rules in a Tsukamoto fuzzy system infers to a crisp output. Accordingly, the Tsukamoto fuzzy system does not need to employ defuzzification.

In this study, the Mamdani method was selected as the most suitable of the three methods considered since it requires relatively simple computational procedures, it has rules which are relatively easy to explain and understand and it is well-suited to human generated input (Mendel,1995). Further, the other two approaches require more resources for them to be practicable, i.e., (a.) The TSK needs the data set of vulnerability components and vulnerability to develop the polynomial function(s) to express their numerical relationship, (b.) The Tsukamoto method also needs develop monotonic membership function, which is not a trivial task. Additionally, the Tsukamoto method is not as transparent as the Mamdani method (Precup and David, 2019).

Consequently, Mamdani method was used to express the relationship (see Eq. 4-1) between vulnerability and its components by the rule in the form of IF…AND…THEN, i.e., IF exposure AND sensitivity AND resilience, THEN vulnerability. Mathematically, it was demonstrated as follows:

$$\mathrm{V} = E \;\; and \;\; S \;\; and \;\; RE \qquad\qquad Eq.4-8$$

More details of how this approach was applied to the vulnerability model can be found in Chapter 7.

4.4 Data collection

Through the identification of the uncertainty-solving approaches described above, the developed vulnerability assessment model has the ability to handle three types of aforementioned uncertainties in the fuzzy environment. In order to test the model relevant data is needed.

The concept of information quality levels (IQLs) was employed to guide data collection (Paterson and Scullion, 1990). With reference to Section 2.2, IQL-1 refers to the most detailed and comprehensive data; IQL-2 the most detailed data; IQL-3 the summary data with classification of values; and IQL-4 the most summary data. Robinson (2008) suggests that data satisfying (a.) IQL1/IQL2/IQL3, (b.) IQL3/IQL4, and (c.) IQL4 are appropriate for (a.) operational level, (b.) programming level and (c.) strategic levels of road asset management respectively. The developed model is intended to be a tool to support tactical (programming) level road asset decision making, i.e. programming level of road management (see Section 1.3 in Chapter) and therefore the data collected should satisfy the requirements of IQL-3/IQL-4.

Where the historical data is unavailable, expert opinion can also be considered as a data source. In particular such information is likely to be required to determine the weights of the determinants of vulnerability (see Eq. 4-1 to Eq. 4-5). Therefore, several criteria for selecting suitable experts were identified, following recommendations suggested by NRC (1997).These are (a) strong relevant expertise including specific expertise of the issues of interest; (b) knowledge of different facets associated with the issues; (c) willingness to act as proponents, to commit time and effect required, to take part in debates and prepare for discussion required; (d) strong communication, interpersonal skills; (e) impartiality, ability to generalise and simplify.

In addition, the size (i.e., the number of experts) and background of the experts are two key points for consideration. The size should be large enough so as to obtain a broad spectrum of opinions as comprehensively as possible, and the background of the experts should be diverse in order to ensure obtained opinions are balanced. Satisfying both aspects enhances credibility the reliability of the data. The literature describes several approaches to select the number of experts. For example, Urdan (2005) suggests that the sample (i.e., the number of experts in this case) should form a normal distribution (bell-shape curve) for the responses if the whole population is large. Additionally, several studies suggest a minimum of 20 samples may be satisfactory (such as Babuscia and Cheung, 2014).

From the literature, five methods for collecting expert opinion were identified. A comparison of their main characteristics, strengths and weaknesses are summarised in Table 4-3. For the purposes of the case studies described in Chapter 7, it was decided that the most appropriate method would be via structured interview because (a.) it can be undertaken in several ways so that it cannot be affected temporally and spatially; (b.) it allows for a set of predefined questions that can assist collecting the relevant data quickly; (c.) it can be used simultaneously to collect qualitative and quantitative data; (d.) the data can be processed easily.

Table 4-3: A comparison of various data collection methods through expert opinion

Methods	The main characteristics of the method	Strengths (S) and weaknesses (W)	References
Focus group (group interview)	• A qualitative research method • It is a meeting of a group including five to twelve participants • It is rarely based on a single topic	(S) It could generate concentrated data quickly (S) It is relatively cheaper compared to many interviews (S) It could be more flexible for data collection due to no strict procedure (W) The conclusion from focus group is limited, as its members cannot be the representatives of larger population (W) Dominant individual could lead the meeting, this causes the deviation of the results	Wilson, (2013); Caporale et al., (2020);

		(W) It could result in conflicts especially between two participants with strong personalities	
Delphi method	• It is an iterative process (i.e., multiple rounds) • It is anonymous process, i.e., all participants do not know other participants' opinions except his/her own • Prior to each round, participants may reconsider their opinions by comparing their own against others • It reaches a general group agreement	(S) The possibility to involve expert worldwide (W) Anonymity and lack of direct interaction amongst participants (W) The length of time to be take, e.g. a three-round process may need 3-4 months (W) Sensitivity to the way the questions are asked	Yousuf, (2007); Fernández-Ávila et al., (2020)
Interview (individual unstructured)	• No predetermined questions	(S) It is easier to build rapport with participants compared to semi-structured and structure interviews (S) It is more flexible for interviewers to ask questions and probe for more details (S) It could reveal the issues interviewers do not consider before (S) It could assist designing more focused semi-structure and structure interviews (W) The processing (e.g. analysis) of data it generates is time-consuming, as even a small study could produce a large amount of qualitative data. (W) It requires interviewer with skills and flexibility due to no set format (W) It is difficult for this interview to take notes	Wilson, (2013)
Interview (individual semi-structured)	• It is conducted, based on extent knowledge about such as a topic, for further details of that topic • It uses open-ended and/or closed-ended questions • It generates qualitative and/or quantitative data	(S) It gives an interviewer greater flexibility (S) It could assist an interviewer to redirect a conversation that is moved away from the main topic (S) It does not strictly require a well-trained interviewer, as a set of predefined questions is available as a guidance	Denscombe, (2010); Wilson, (2013)

		(W) There could be interviewer effect, i.e., the background, age, gender or race etc. of the interviewer may have negative impact the interviewee's willingness to give information (W) The mixed qualitative and quantitative data the interview generates could take long time to process and analyse	
Interview (individual structured)	• The questions are pre-defined and fixed • It includes open-ended and closed-ended questions • It generates qualitative and/or quantitative data	(S) It can be carried out by various ways, such as by telephone, the internet, face to face etc. (S) Relatively untrained interviewers can be used (S) Data can be more easily analysed as most questions give structured answers (W) It needs solid background during questionnaire design stage (W) It needs interviewees to behave consistently. This is not easy, in particular they are tried (W) Interviewees may play a passive role	Wilson, (2013)

4.4.1.1 Questionnaire

The structured interview was implemented via a questionnaire to obtain data relating to:

1. Vulnerability identification (section 4.4.1.1).
2. Vulnerability analysis (section 4.4.1.2).

4.4.1.1.1 Vulnerability identification

It was decided to carry out the interviews with the aid of a questionnaire rather than simply sending out the questionnaires in the post or via email as this would enable interaction between the interviewer and interviewee. This would allow for in-depth conversation of relevant issues, enable the interviewee to ask questions of clarification and would also enable more information to be collected, for example on the nature of the identified hazardous events. Accordingly, it was anticipated that this approach would allow for improved quality of response.

The collection of the data related to vulnerability identification refers to (a.) the confirmation of the hazardous events derived from the literature review (see Chapter 5), (b.) the identification of new hazardous events, and (c) confirmation of the hazardous event identified in (a) and (b.). Therefore, this collection procedure included two sequential rounds, i.e., (a.) and (b.) and thereafter (c.) the two-round-procedure can solve the subjectivity that normally causes insufficient validity and reliability when using qualitative methods (Burns, 2000). Furthermore, the use of a number of experts with different backgrounds and disciplines could achieve triangulation (Bergman, 2008). Based on this, this procedure required that only hazardous event confirmed by at least two experts at identification phrase were further taken into account in the analysis step, unless there was a strong evidence from literatures to support its further consideration.

4.4.1.1.2 Vulnerability analysis

After the vulnerability identification process, the experts were asked to estimate the frequencies of occurrence of confirmed hazardous events and corresponding consequences. Although Silverman (2009) states that the structural bias and false representation may occur in the vulnerability analysis, i.e., the analysis results only reflect the standpoint of the experts who answer the questionnaire and researcher in the analysis. Nevertheless, Creswell et al.

(2003) suggests that this problem can be solved if a qualitative approach is used (i.e., the confirmation of hazardous event by experts) as utilised above in this research.

In addition to the estimation of frequency and consequence of hazardous events, experts were also required to estimate the numerical range of parameters in the modelled indicators related to sensitivity and resilience, and to undertake pairwise comparison for the relative weights of vulnerability determinants.

4.5 Summary

This chapter established a methodology to develop an AHP based vulnerability assessment model with the capability to deal with uncertainty. First, the research methodology was developed to describe the methods used to conduct this research. Four sequential stages were described, namely (a.) literature review to identify the research gap for road investment prioritisation, (b.) the identification of relevant method/techniques for the development of an AHP based vulnerability assessment model, (c.) the identification of uncertainty related techniques/approaches (i.e., fuzzy logic) to enable the vulnerability model with ability to deal with uncertainty, and (d.) data collection approaches for the vulnerability model.

Secondly, an AHP based vulnerability assessment model was developed. The model considers exposure, sensitivity and resilience as three components of a rural community road access vulnerability and establishes a relationship between vulnerability and its components. Three kinds of uncertainty were identified in relation to: and expert judgement, to the identification of the weights of the determinants through the pairwise comparison process and vulnerability aggregation uncertainty. Fuzzy concept related techniques were identified to address these elements of uncertainty.

As far as data collection is concerned, the structured individual interview process was identified as a suitable means to collect expert opinion. Additionally, trapezoidal fuzzy number was identified to process the data deriving from the interview.

The next chapter will further develop the vulnerability assessment model in terms of the identification of the vulnerability determinants and analysis of the determinants identified.

CHAPTER 5 VULNERABILITY IDENTIFICATION AND ANALYSIS

5.1 Introduction

Following a review of the literature three determinants for rural community road access vulnerability, namely exposure, sensitivity and resilience, were identified and defined in Chapter 4 (see Figure 4-2). This chapter in Sections 5.2.1, 5.2.2 and 5.2.3 describes the further disaggregation of exposure, sensitivity, and resilience respectively.

Additionally, an approach which scores three determinants and their disaggregation identified in Sections 5.2.1, 5.2.2 and 5.2.3 and normalises these scores was adopted. Such an approach has been found to increase the acceptability of the model by practitioners since it is relatively easy to understand and transparent (Niemeijer, 2002). This approach may also decrease the possibility of the overconfidence of participants for providing data, especially when absolute values of determinants are provided (Preston et al., 2011). Further, this comparative approach facilitates the quantification of acceptable limits of the vulnerability index (e.g. high, medium, and low; Burrow, 2014) and allows for road investments to be prioritised transparently to those communities with higher scores.

5.2 Vulnerability identification and analysis

Four major types of vulnerability model are described in the literature (see Chapter 3). From these the Expanded Vulnerability (EV) model was chosen for the task at hand, as it allows the most comprehensive understanding of vulnerability (Turner et al., 2003). In the EV model, the vulnerability of an entity (such as a community) is regarded as being composed of three dimensions as stated in Chapter 4: the exposure of the entity to threats, its susceptibility to such exposure, and its capacity to withstand the threats. Accordingly, rural community road access vulnerability is described in this chapter in terms of exposure, sensitivity, and resilience. The disaggregation of the three components is demonstrated and further elaborated in Figure 5-1.

5.2.1 Exposure (*E*)

In the EV model (Turner et al., 2003), exposure refers to the component(s) of a system (such as a community) that is at risk when a specific negative factor (such as a geo-hazard (e.g. a flood)) impacts the system. In this study of assessing rural community road access vulnerability, the negative agent was defined to be one or more geo-hazards that cause a road to deteriorate or become impassable. Such hazards include direct rainfall/runoff, erosion, flooding in streams and rivers, sediment transport and landslide (Hearn, 2014). This study assumes that the community is only served by one road leading to outside world is at risk.

The direct impact of the exposure was defined to be (a) deteriorated roads serving a rural community and/or (b) impassable roads due to the occurrence of geo-hazards. In other words, the community is at risk of (a) having undesirable road conditions or/and (b) loss of road access both of which impact the ability of the community to access amenities safely, reliably, and at reasonable cost (i.e., affordably).

In Chapter 4, Table 3-3 in Section 3.3 summarises the physical impacts of geo-hazards on road asset. Six socio-economic impacts of poor road condition and loss of access were identified from the systematic review of the impacts of rural roads carried out by Hine et al. (2015). These are associated with travel and transport activities related to agriculture, education, employment, health, income and consumption, and marketing (see Section 1.1 in Chapter 1). For this research, these have been disaggregated into 26 rural-road-investment-related benefits based on the work by Odoki et al. (2008), as illustrated in Figures 5-2 (a) – 5.2 (c).

Based on Eq. 4-2 exposure can be calculated through summing poor road condition and access loss risks both determined by summing their own six impacts above. Such impacts are considered to be six risk (or hazardous) event groups (HG) where each is obtained aggregating their corresponding hazardous events (HE) (i.e., 26 road investment related benefits, see Figure 5-2 (a) – 5.2 (c)). Therefore, the risk level of a hazardous event i, E_{HE_i}, is initially calculated, based on Eq. 4-3, using the equations as:

$$E_{HE_i}^{PRC} = P_{HE_i}^{PRC} \times I_{HE_i}^{PRC}, i = 1,2, \dots n, \qquad Eq. 5-1$$

$$E_{HE_j}^{RAL} = P_{HE_j}^{RAL} \times I_{HE_j}^{RAL}, j = 1,2, \dots n, \qquad Eq. 5-2$$

where $E_{HE_i}^{PRC}$ is the risk level of hazardous event i resulting from poor road condition, and $E_{HE_j}^{RAL}$ is the risk level of hazardous event j resulting from a loss of road access provision.

$P_{HE_i}^{PRC}$ and $P_{HE_j}^{RAL}$ are the probabilities (i.e., frequencies) that a community is affected by hazardous event i or j due to poor road condition or loss of road access provision respectively. $I_{HE_i}^{PRC}$ and $I_{HE_i}^{RAL}$ are the consequences of hazardous event i or j (measured in terms of number of people affected or increases in travel time).

$E_{HE_i}^{PRC}$ and $E_{HE_j}^{RAL}$ are normalised as follows:

$$E_{HE_i}^{PRC'} = \frac{E_{HE_i}^{PRC}}{Max\ E_{HE_i}^{PRC}} \qquad Eq. 5-3$$

$$E_{HE_j}^{RAL'} = \frac{E_{HE_j}^{RAL}}{Max\ E_{HE_j}^{RAL}} \qquad Eq. 5-4$$

Where $Max\ E_{HE_i}^{PRC'}$ and $Max\ E_{HE_j}^{RAL'}$ are the maximum value of risk level of $E_{HE_i}^{PRC}$ and $E_{HE_j}^{RAL}$ for the communities considered in a comparative analysis.

From the above, the risk level of hazardous event group k, E_{HG_k}, can be calculated using the following equations:

$$E_{HG_k} = W_{PRC} \sum_{i=1}^{n} E_{HE_i}^{PRC'} \times W_{E_{HE_i}^{PRC'}} + W_{RAL} \sum_{j=1}^{n} E_{HE_j}^{RAL'} \times W_{E_{HE_j}^{RAL'}} \qquad Eq. 5-5$$

where $W_{E_{HE_i}^{PRC'}}$ and $W_{E_{HE_j}^{RAL'}}$ are the relative importance of hazardous events i

and $j, \sum_{i=1}^{n} W_{E_{HE_i}^{PRC'}} + \sum_{j=1}^{n} W_{E_{HE_j}^{RAL'}} = 1$. W_{PRC} and $W_{RAL}$are the relative importance of poor road condition and loss of road access respectively, to the risk level of hazardous event group k. $W_{PRC} + W_{RAL} = 1$;

Whence the overall exposure level of the community, E_{Com}, is given by:

$$E = E_{Com} = \frac{W_{E_{Com}} \times \sum_{k=1}^{n} E_{HG_k} \times W_{HG_k}}{MaxW_{E_{Com}} \times \sum_{k=1}^{n} E_{HG_k} \times W_{HG_k}} \qquad Eq. 5-6$$

Where W_{HG_k} is the relative importance of hazardous group k and $\sum_{k=1}^{K} W_{HG_k} = 1$. $W_{E_{Com}}$ is the relative importance of exposure compared with sensitivity (W_S) and resilience (W_{RE}) described in Sections 5.2.2 and 5.2.3., and $W_{E_{Com}} + W_S + W_{RE} = 1$. $MaxW_{E_{Com}} \times \sum_{k=1}^{n} E_{HG_k} \times W_{HG_k}$ is the maximum value of overall exposure level for the communities considered.

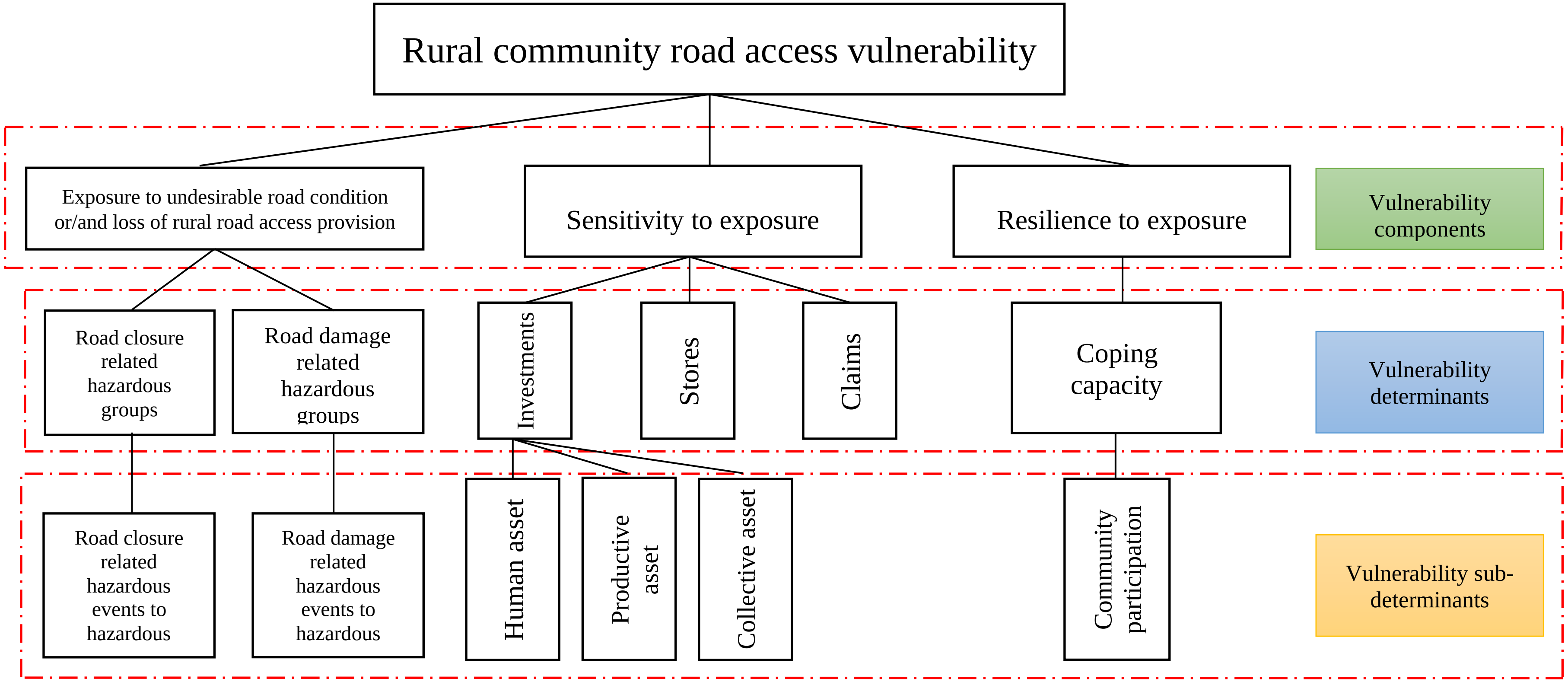


Figure 5-1: The identification of rural community road access vulnerability

5.2.2 Sensitivity (*S*)

Sensitivity refers to a dose-and-response relationship between being exposed and the resultant impact of an exposed system (Fussel and Klein, 2006). Dose, in this study, was considered to be an amount of exposure, i.e., the amount of road damage and/or the number of days the road is closed, while response was defined as the ability of a community to cope with the dose. Hence, a community's sensitivity is associated with its existing coping mechanism determined by its social and biophysical capital (Turner et al., 2003). In other words, the more capital a community has that can be mobilised to cope with difficulties, the stronger it's coping capacity, the more impacts the community can absorb, thereby the less the community is sensitive. The coping capacity refers to a short-term capacity to survive during or immediately following the exposure (Birkmann, 2007)

As Turner et al. (2003) suggests, this capital as far as communities is concerned is related in part to entitlement. Entitlement refers to the legal and customary rights of a social unit (such as a community) to acquire food and other necessities, and is determined by the unit's endowment (such as its available labour force, available skills or road access to services or facilities (Sen, 1983)). For example, famine may result from a community's inability to acquire access to food by legal and customary ways rather than absolute shortage of food stock. Hence, the concept of assets alluded to in Sen's entitlement theory was utilised to represent the relationship between entitlement and endowment. In the analysis of famine sensitivity, Swift (1989) asserts that assets can be used to both create more assets and cope with difficulties in a period of hardship. Accordingly, following the associated review of the literature summarised in Table 3-4 in Chapter 3, a rural community's sensitivity was determined through its investments, stores and claims assets. These determinants are summarised in Figure 5.1 and are further described below.

Based on Eq. 4-4, sensitivity of a community was calculated as:

$$S = \frac{W_S \times \ (W_{In} \times In + W_{St} \times St + W_{Cl} \times Cl)}{Max\ W_S \times \ (W_{In} \times In + W_{St} \times St + W_{Cl} \times Cl)} \qquad \text{Eq.}\, 5-7$$

Where In is investments, St is stores and Cl is claims to be elaborated below. W_{In}, W_{St} and W_{Cl} are the relative importance of investments, stores and claims and $W_{In} + \ W_{St} + \ W_{Cl} = 1$. W_S is the relative importance of sensitivity. $Max\ W_S \times \ (W_{In} \times In + W_{St} \times St + W_{Cl} \times Cl)$ is the maximum of quantity of sensitivity for all communities considered.

5.2.2.1 Investments (In)

Decreased access to resources, limited diversity of economic assets that may cause inadequate coping behaviour typically creates social vulnerability (Adger, 1999; Fielding, 2012). Accordingly, investments, which are profitable assets that generate income and reduce

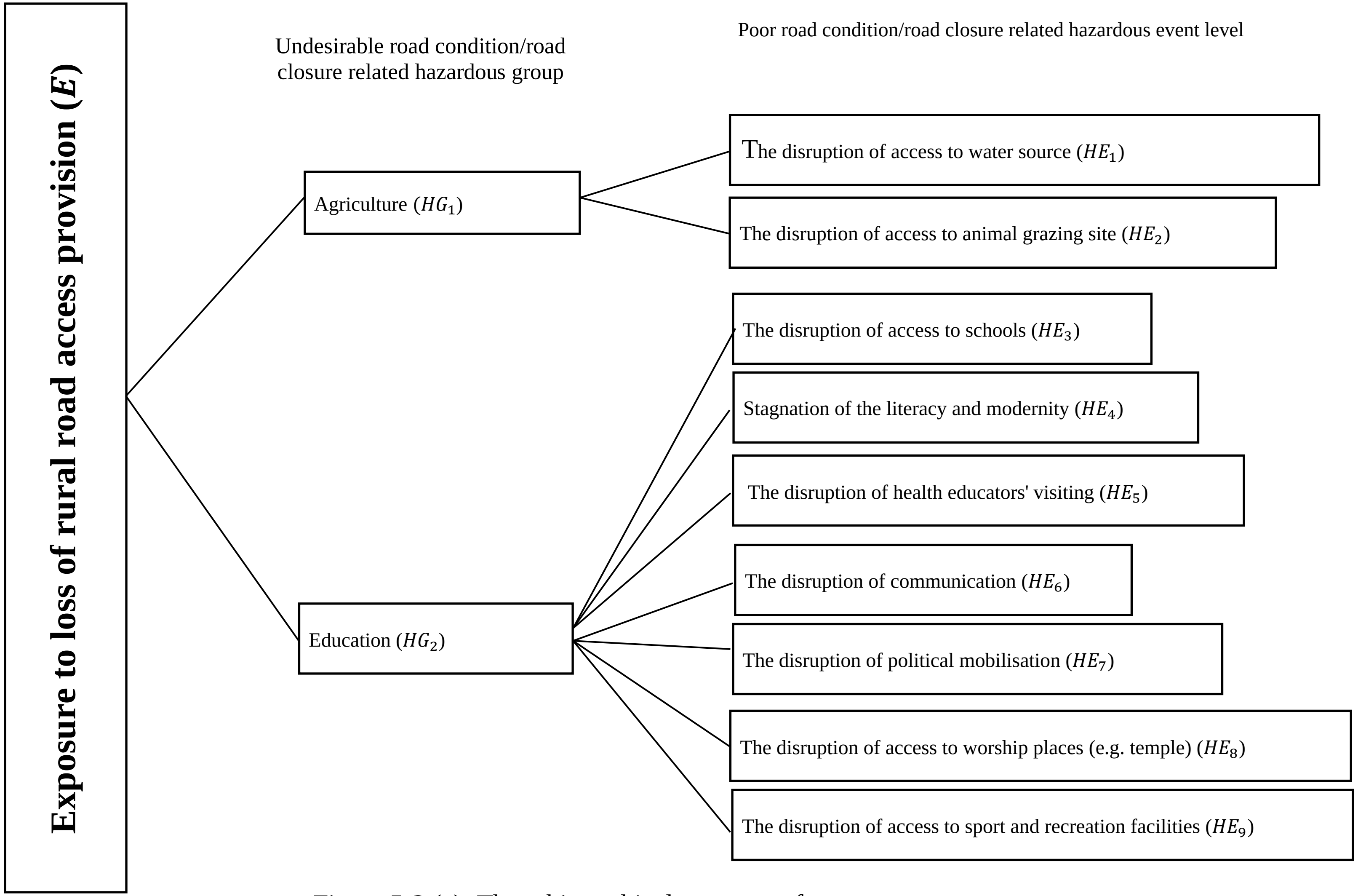


Figure 5-2 (a): Three hierarchical structure of exposure

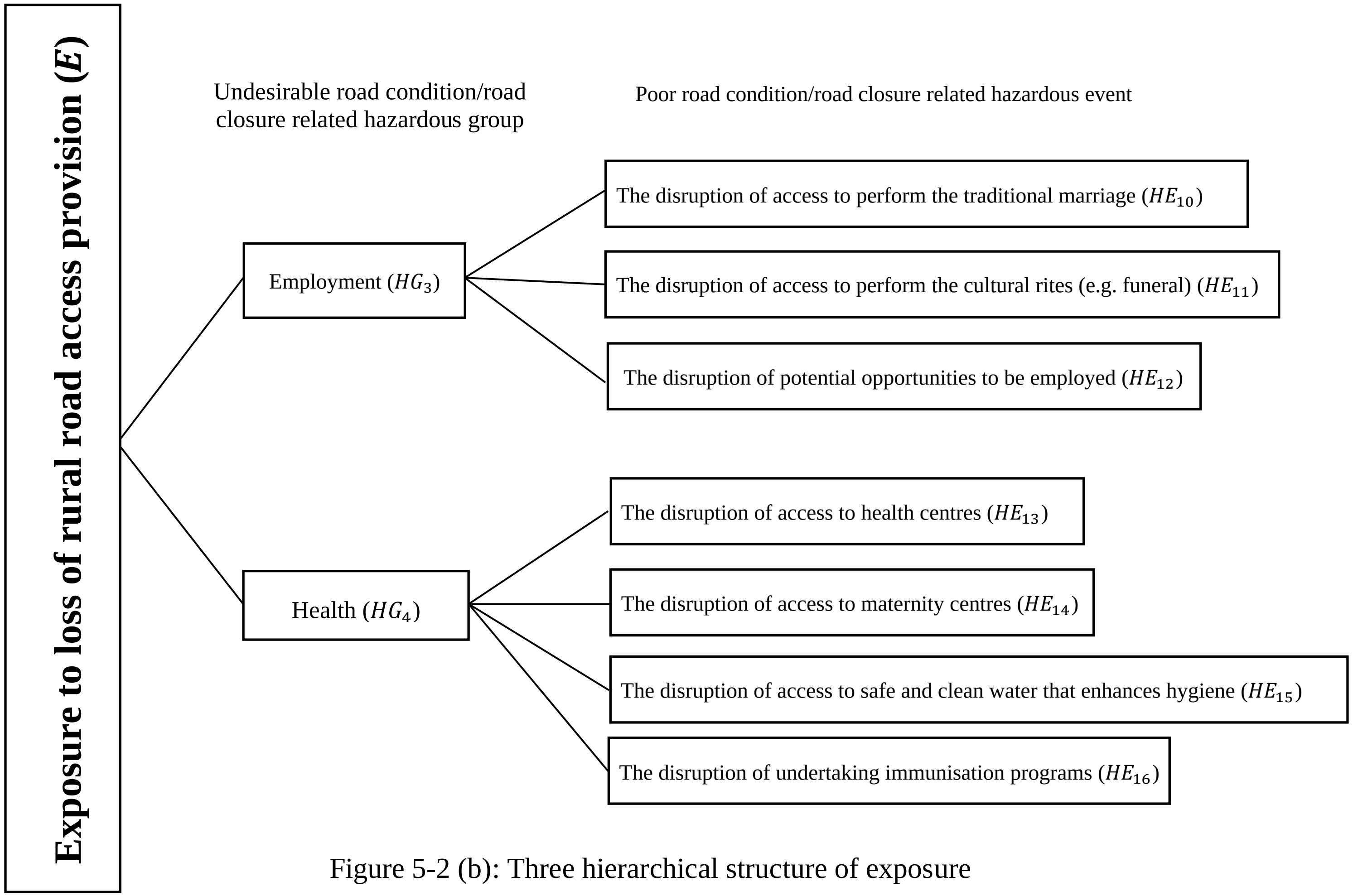


Figure 5-2 (b): Three hierarchical structure of exposure

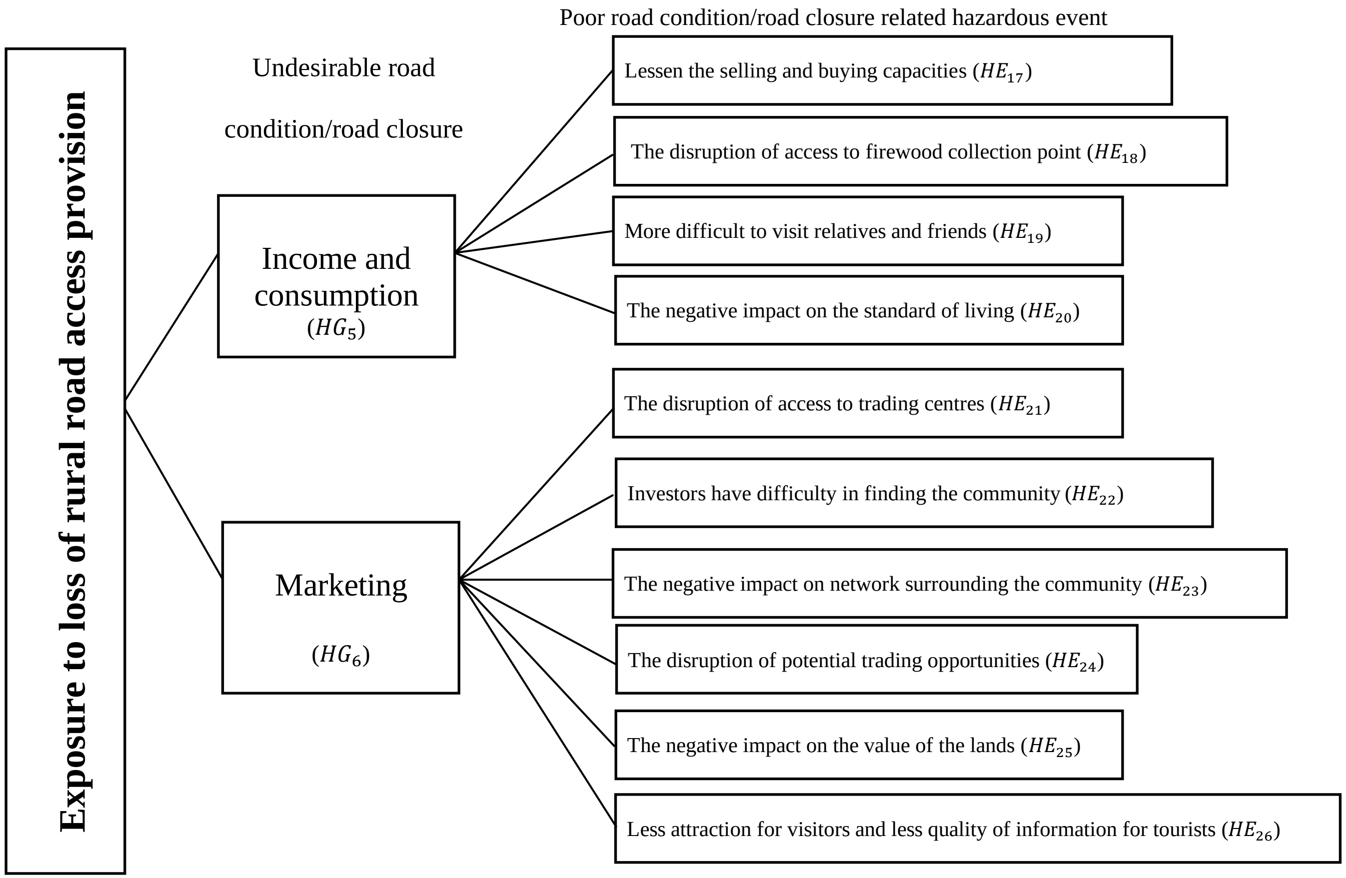


Figure 5-2 (c): Three hierarchical structure of exposure poverty, can be regarded as determinants of rural community sensitivity to exposure. Based on the work by Swift (1989) investments have been classified in this research into human, productive, and collective assets (see Figure 5-3).

Based on Eq. 4-4, a community sensitivity in terms of investments was calculated as:

$$In = W_{Ha} \times Ha + W_{Pa} \times Pa + W_{Ca} \times Ca \qquad \text{Eq. } 5-8$$

Where Ha is human assets, Pa is productive assets and Ca is collective assets to be elaborated below. W_{Ha}, W_{Pa} and W_{Ca} are the relative importance of human assets, productive assets and collective assets and $W_{Ha} + W_{Pa} + W_{Ca} = 1$.

5.2.2.1.1 Human assets (Ha)

A household's income level in general determines its capacity to recover from a disaster (Flanagan et al., 2011). A high income correlates with savings and insurance policies; thus, a household with high income is typically less vulnerable than one with a lower income and tends to be able to recover faster. Those members of rural communities which are regarded as having a low income are women, children, the elderly and the disabled (Buor, 2003 Garcia and Fares, 2007; Valdés et al., 2009; Klasen et al., 2011). Therefore, those communities with greater numbers of women, children, the elderly and the disabled, may be regarded as having a lower level of income, all other things being equal. Similarly, communities with lower populations may also be regarded as having a lower income potential. Such communities are typically located in isolated areas with sparse facilities, thus implying a lower income level (Porter, 2013; Cutter et al., 2014).

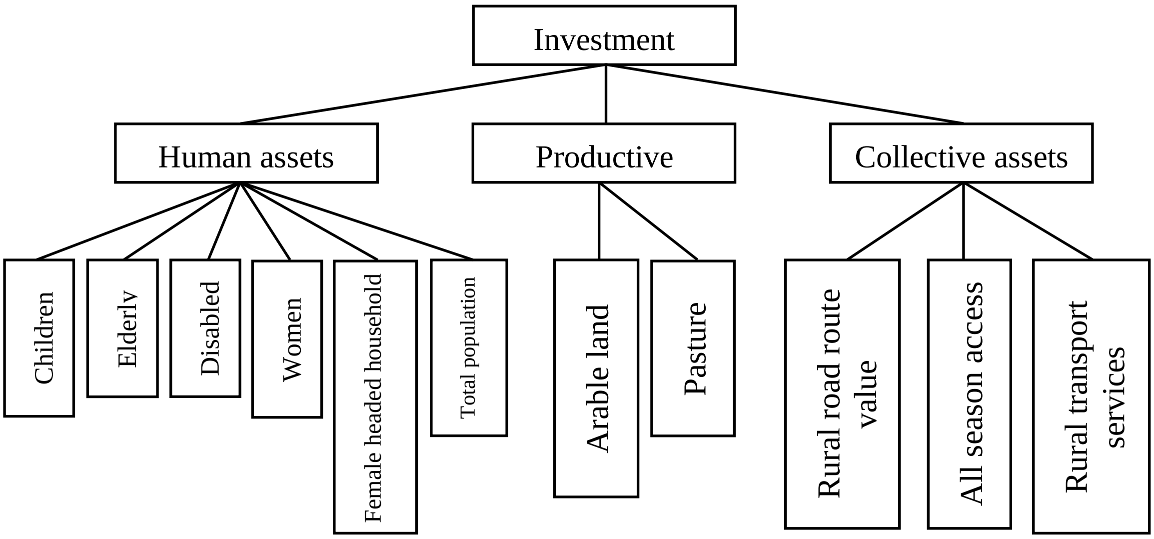


Figure 5-3: Three-hierarchical structure of investment

- *Children* (Ch)*, the elderly* (El)*, and the disabled* (Dis)

Children (those under 16 years old), the elderly (those over 65 years old), and the disabled are typically excluded from the labour force due to lack of skills or physical constraints; they are not involved in paid jobs (Morrow, 1999; Garcia and Fares, 2008; Valdés et al., 2009; Geest, 2010; Guarcello, 2012; Lundgren and Jonsson, 2012; Norman, 2013; Khan et al., 2017). Access to important services such as healthcare can be challenging for this group, due to the necessary pedestrian mobility required as a result of the high cost of transport services (Porter, 2013). This reinforces their poverty.

- *Women* (Wo) *and female headed households* (Fh)

Women in developing countries in general face discrimination in the workforce in the form of lower remuneration for similar work and exclusion from higher paying jobs (Klasen et al., 2011). Furthermore, women typically have limited access to resources and rights (such as land and livestock) for cultural reasons in many developing countries, especially in rural areas (Blaikie et al., 1994; Hewitt, 1994; Enarson and Morrow, 1999; Enarson and Scanlon, 1999; Morrow and Philips, 1999). Thus, they cannot improve their income level through agricultural activities, which is especially relevant in rural areas where agriculture dominates the economy (World Bank, 2008). Women also cannot use animals to cultivate land due to physical and cultural constraints, meaning that they must rely on men for agricultural activities (Burrow, 2014). This leads to their receiving an unfair proportion of the crop production. Additionally, female traders who typically lack means of transport tend to be restricted to within-village transactions, reducing their incomes and independence (Ruthven and Koné, 1995). Moreover, female-headed households are preoccupied with meeting subsistence and domestic needs to ensure their survival, and thus have limited opportunity to engage in income-generating activities (Barwell, 1996; Davies et al., 2000; Ginn, 2003). This is because this kind of household typically faces the absence of a male partner, a lack of access to IMT (Intermediate Means of Transport), and the need to travel to distant fields for cultivation, all of which contribute to a heavier transport burden.

Thus, the total population (Tp) of a community was considered to be a positive determinant of sensitivity whilst the number of children, elderly, disabled, women and female headed household were treated to be the negative determinants of sensitivity (see Figure 5-3). Consequently, the greater the total population of a community is, the less the sensitivity of the community and the greater the number of children, elderly, disabled, women and female headed household, the more the greater sensitivity.

Based on Eq. 4-3, a human assets indicator, Ha, for a community was developed as follows:

$$Ha = 1 - \frac{W_{Tp} \times Tp - W_{Ch} \times Ch - W_{El} \times El - W_{Dis} \times Dis - W_{Wo} \times Wo - W_{Fh} \times Fh}{Max(W_{Tp} \times Tp - W_{Ch} \times Ch - W_{El} \times El - W_{Dis} \times Dis - W_{Wo} \times Wo - W_{Fh} \times Fh)} \quad Eq. 5-9$$

Where $Ch = N_{ch} - N_{ch^{Dis}}$ is the number of children without disability in the community, N_{ch} is the total number of children, whilst $N_{ch^{Dis}}$ is the number of disabled children. $El = N_{el} - N_{el^{Dis}}^{Ma} - N_{el^{Dis}}^{Wo}$ is the number of elderly without disability, N_{el} is the total number of elderly, $N_{el^{Dis}}^{Ma}$ is the number of disabled elderly man, $N_{el^{Dis}}^{Wo}$ is the number of disabled elderly women. $Wo = N_{wo} - N_{Dis}^{Wo} - N_{Fh}$. N_{Dis}^{Wo} is the number of women with disability, N_{Fh} is the number of female-headed household. Dis is the number of population with disability, $Dis = N_{ch^{Dis}} + N_{el^{Dis}}^{Ma} + N_{el^{Dis}}^{Wo} + N_{Dis}^{Wo}$. $Max(W_{Tp} \times Tp - W_{Ch} \times Ch - W_{El} \times El - W_{Dis} \times Dis - W_{Wo} \times Wo - W_{Fh} \times Fh)$ is the maximum value for the community considered.

5.2.2.1.2 Productive assets (Pa)

A productive asset is that which can produce income. For rural communities in developing countries, which are primarily agrarian, Davis et al. (2017) suggests that a suitable measure of productive assets are the amount of pasture and arable land, since livestock and crop production are the major income sources for rural households. For example, Burrow's study (2014) reveals that 90% or more of the income source for seven different communities in rural Ethiopia is derived from cultivated land and livestock, with two of these communities acquiring 40% or more of their income from livestock alone.

Thus, rural households typically subsist on their crops and livestock, and any disruption to crop and livestock production can make them vulnerable. For example, studies on Africa and Asia (Swift, 1989) have shown that the decrease in the market exchange rates of livestock and cereal grains had a significantly negative impact on the subsistence of pastoralists, especially in areas with a bartering culture. As calories of animal origins are normally more expensive than calories of vegetable origins, pastoralists can acquire cereals at a substantial discount in exchange for animal products. However, this makes them more vulnerable to changes in the animal-to-cereal price ratios. If animal prices fall (due to increased supply, lower demand, or perhaps a lower price being offered for animals in poor condition), pastoralists can experience an exchange crisis, even if the price of cereals has not risen. Often, however, the drivers of decreased animal prices – especially drought and the associated poverty that, in turn, leads to more animal sales – can also cause cereal prices to increase. Hence, the amount of pasture and arable land of a community were used in this work as positive determinants of sensitivity illustrated in Figure 5-3. Consequently, the more the amount of pasture and arable land of a community the less the sensitivity.

Based on Eq. 4-4, a productive assets indicator, Pa, for a community was developed as follows:

$$Pa = W_{Li} \times Li \; + \; W_{Cr} \times Cr \qquad Eq. 5-10$$

Where Li is the livestock indicator, Ar is the crop indicator, w_{Li} and w_{Cr} are the relative importance of the livestock and crop indicators respectively, and $w_{Li} + w_{Cr} = 1$.

In order to satisfy that the higher level of livestock and crops leads to the higher level of sensitivity as informed in Eq. 5-7, Eq. 5-8 and Eq. 5-10, the livestock indicator, Li, and crop indicator, Cr, were developed as:

$$Li = 1 - \frac{\frac{Al \times Il}{Tp}}{Max \frac{Al \times Il}{Tp}} \qquad Eq. 5-11$$

Where Al is the area of land grazed by the livestock (ha) and Il is the percentage of a community's income received from livestock.

$$Cr = 1 - \frac{\frac{Ac \times Ic}{Tp}}{Max\ \frac{Ac \times Ic}{Tp}} \qquad Eq. 5-12$$

Where Ac is the area devoted to farming (ha) and Ic is the percentage of the community's income received from farming.

5.2.2.1.3 Collective assets (Ca)

Rural communities in developing countries are typically isolated from markets and economic opportunities and lack access to social services, and are served by roads in poor condition and/or lack access to all-season roads. Consequently, they have relatively high costs of owning and operating transport services (World Bank, 2008; Faiz, 2012; Porter, 2013; Banwatt, 2014; Hine et al., 2015; Limi et al., 2016). This means that socio-economic activities involving travel (i.e., the personal movement) and transport (i.e., carrying out goods and commodities) entail more time and higher costs, affecting a community' income levels and, in turn, its income-related capacities to cope with hazardous events (see Section 1.1 in Chapter 1).

In order to capture the above in the model it was decided to include the value of the rural road route from a community to local amenities, the availability of all-season roads, and the availability of transport services. Based on the Eq. 4-4, the collective assets of investments for a community was calculated as:

$$Ca = W_{Rv} \times Rv + W_{RAI} \times RAI + W_{Ts} \times Ts \qquad Eq. 5-13$$

Where Rv is the rural road route value indicator (%), RAI is the all season access index (%), Ts is the rural transport service indicator; w_{Rv}, w_{RAI} and w_{Ts} are relative weights of the rural road route value , the rural access index and the rural transport service indicators respectively, and $w_{Rv} + w_{RAI} + w_{Ts} = 1$.

- ***Rural road route value (Rv)***

A number of studies have demonstrated that transport costs are directly related to road condition (see for example, Burrow et al. 2018). Ogunsanya (1988) demonstrates that rough roads are a key factor in the damage of perishable crops, causing loss to the farmers and Paul et al. (2009) show that poor road condition and the resulting high cost of transporting agricultural imports and exports lead to high transaction costs, constraining agricultural productivity and growth in many rural sub-Saharan countries. This in turn lowers the income level in the agriculturally dominated areas of these countries. Further, in low-income counties, most rural roads are built from soil or gravel, due to the difficulty of justifying the expense of paved roads for a low level of traffic (Wattam and IT Transport Ltd., 1998). This means that they are more prone to damage by the environment, especially in the context of the changing climate (Burrow, 2014; Hearn, 2014). Therefore, rural road route is identified as a positive determinant of collective assets in sensitivity demonstrated in Figure 5-3. In other words, the better the road route condition of a community, the less the sensitivity.

In order to capture both the effect of the condition of the road on increased transport costs and the intrinsic value of the road in the developed vulnerability model, it was decided to use a valuation approach. The depreciated replacement cost (DRC) method (see Figure 5-4) was chosen to this end since it takes into account road condition and it is relatively straightforward and easy to obtain the required data (Robinson, 2008). DRC is defined as the gross replacement cost (GRC) of a specific rural road route after deducting consumption to reflect the remaining economic life of the route, i.e., the total cost of replacement of the rural road route (Robinson, 2008). DRC equals GRC minus consumption, i.e., depreciation. According to the Roads Liaison Group (2005), road depreciation can be treated by either the average of a rolling estimate of the maintenance and renewal expenditures required to keep the road's defined service level within the forecast period or by the expenditure required to maintain the route and bring it to the original (or new) condition. For this research it was decided to use the expenditure required to maintain the route and bring it to a new condition. The concept of DRC is demonstrated in Figure 5-4.

Accordingly, for this work a DRC ratio representing the current asset value of a road route from the community to a specified amenity was developed as follows:

$$DRC_i = \frac{GRC_i - RC_i}{GRC_i} \qquad Eq. 5-14$$

Where GRC_i is the GRC calculated by the total area of the road route from a rural community to the amenity i multiplied by the unit cost of construction, RC_i is the cost of restoring the route, from the community to the amenity i, to its new condition. Costs related to GRC_i and MC_i are based on current market prices.

In order to satisfy that the higher level of rural road route value leads to the higher level of sensitivity as revealed in Eq. 5-7, Eq. 5-8 and Eq.5-13, the rural road route value indicator, Rv, was defined as:

$$Rv = 1 - \frac{\frac{\sum_{i=1}^{N} w_i DRC_i}{Tn^{ru}}}{Max \frac{\sum_{i=1}^{N} w_i DRC_i}{Tn^{ru}}} \qquad Eq. 5-15$$

where N is the number of amenities considered, DRC_i is the current asset value of a road route from a community to an amenity i (see Section 5.2.2.1.3), Tn^{ru} is the total number of road route users, w_i is relative importance of the route to an amenity i, $\sum_{i=1}^{N} w_i = 1$, and $Max \frac{\sum_{i=1}^{N} w_i \ DRC_i}{Tp}$ is the maximum of quantity for all communities considered in a comparative analysis.

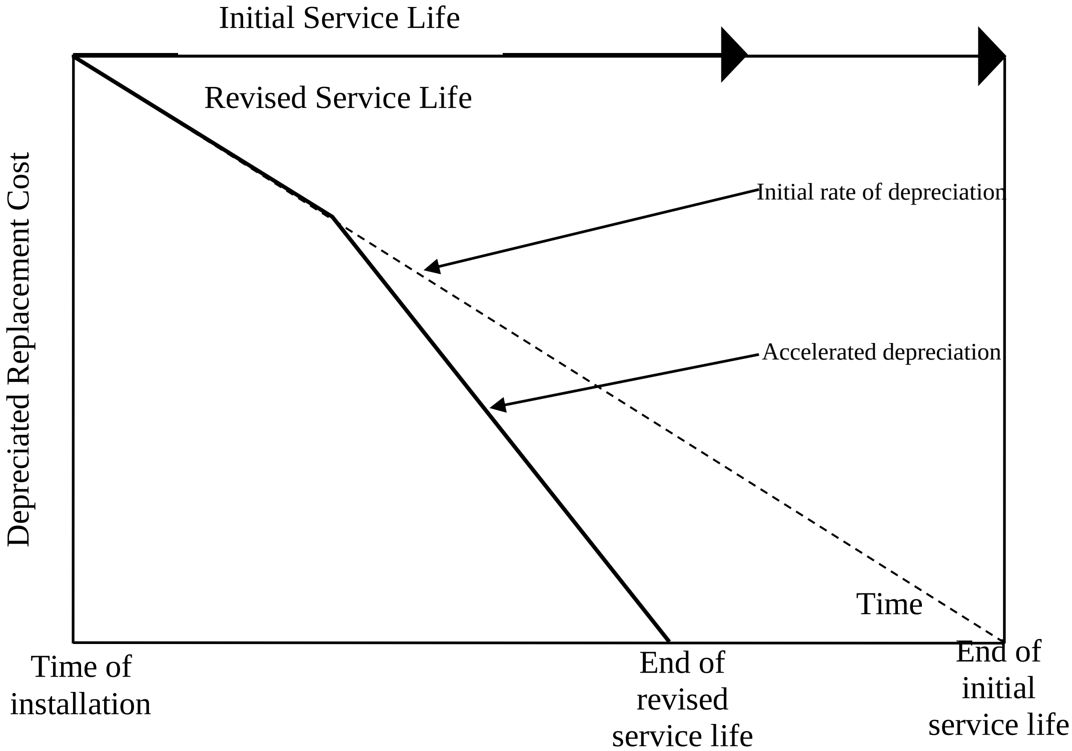


Figure 5-4: Depreciation profile (source: modified from Robinson, 2008)

- ***All season access (Rural access index (RAI))***

All season access herein refers to the ability to access an all-season road (see Section 1.1 in Chapter 1). A number of studies has shown that villages in developing countries with lower all-season access tend to socially and economically constrained since such villages are unable to access markets and services during the rainy seasons. For example, Limi et al. (2016)

demonstrated that for villages in rural Kenya, Mozambique and Uganda the lower the all-season access the higher the poverty. Thus, a low level of all-season access could restrict a community's coping strategies. Consequently, all season access was considered to be a determinant of collective assets in sensitivity (see Figure 5-3). Accordingly, the fewer the population of a community that is able to access an all-season road, the higher the sensitivity of the community.

For the purposes of this project the new rural access index (RAI) developed via Limi et al. (2016) was used as a measure of all-season access. RAI is given by the proportion of people out of the total rural population with access to an all-season road in good or fair condition within a radius of 2 km (equivalent to a 20-25-minute walk). The new RAI was used instead of the original RAI (developed by Roberts et al. 2006), as the original RAI does not consider the condition of the all-season road. Consequently, the original RAI does not necessarily measure transport connectivity since the all-season road may be in poor condition or impassable.

In order to satisfy that the higher value of RAI leads to the higher value of sensitivity, an all-season access indicator was developed as follows:

$$RAI = 1 - \frac{Tp^{2km}}{Tp} \qquad Eq. 5-16$$

where Tp^{2km} is the number of the people who reside within 2 km of the nearest road in good or fair condition in a rural community.

- ***Rural transport services (Ts)***

As discussed in Section 1.1 in Chapter 1, good (i.e., safe, affordable and reliable) rural transport services have been found to aid the efficiency of rural travel and the movement of goods (i.e., social and economic activities) for example by decreasing the time and effort needed to transport agricultural imports and exports (Anchirinah et al., 2008); reducing damage to agricultural produce (Porter, 2013); facilitating access to market and social amenities (HLAGST, 2016); lessening the burden of firewood and water collection (Porter, 2002); contributing to livelihood diversification (Barrett et al., 2001; Gladwin et al, 2001; Porter, 2002); speeding access to maternal health services (Porter, 2013); enabling fast and easy travel to paid employment (Barwell, 1996); and improving schooling (Danso-Wiredu, 2014) (more information on the impact of poor rural transport services can be found in Table 3-4 in Chapter 3).

Consequently, the availability of rural transport services was chosen as a positive determinant of the sensitivity for a community (see Figure 5-3). The worse the availability of rural transport services the higher the community's sensitivity.

In order to satisfy that the higher level of availability of rural transport services leads to the lower level of sensitivity, a rural transport service indicator was developed as follows:

$$Ts = (1 - Ts_c) \times w_c + (1 - Ts_P) \times w_p \qquad Eq. 5-17$$

Where Ts_c and Ts_P are availability of rural transport services for cargo and passenger respectively. $Ts_c = \frac{\frac{\sum_{i=1}^{N} Q_i^c \times Nt_i^c \times Ml_i \times Nd \times w_i^{Ts^c}}{Tp}}{Max \frac{\sum_{i=1}^{N} Q_i^c \times Nt_i^c \times Ml_i \times Nd \times w_i^{Ts^c}}{Tp}}$ and $Ts_c = \frac{\frac{\sum_{j=1}^{M} Q_j^p \times Nt_j^p \times Mp_j \times Nd \times w_j^{Ts^p}}{Tp}}{Max \frac{\sum_{j=1}^{N} Q_j^p \times Nt_j^p \times Mp_j \times Nd \times w_j^{Ts^p}}{Tp}}$. N is the number of types of cargo-related transport services, Q_i^c is the quantity of i type of transport service, Nt_i^c is the average number of trips of the transport service, i, to or from a rural community for transporting cargo per day, and Ml_i is the maximum load per trip for the transport service i (Kg). Nd is the number of days in a given year when any transport service is serving the community, w_i is the relative importance of ith cargo-related transport service, and $\sum_{i=1}^{N} w_i^{Ts^c} = 1$.

$Max\, \frac{\sum_{i=1}^{N} Q_i^c \times Nt_i^c \times Ml_i \times Nd \times w_i^{Ts^c}}{Tp}$ is the maximum score of the cargo transport service for all communities considered in a comparative analysis. w_c is the relative importance of the cargo-related transport services compared with passenger-related transport services, w_p, and $w_c + w_p = 1$. M is the number of types of passenger-related transport services, Q_j^p is the quantity of j type of transport service, Nt_j^p is the number of trips of transport service, j, to or from a rural community for transporting people per day, Mp_j is the maximum number of people per trip for transport service j. w_j is the relative importance of the jth passenger-related transport service, $\sum_{j=1}^{N} w_j^{Ts^p} = 1$, and $Max\, \frac{\sum_{j=1}^{N} Q_j^p \times Nt_j^p \times Mp_j \times Nd \times w_j^{Ts^p}}{Tp}$ is the maximum score of passenger-related transport services for all considered communities

5.2.2.2 Stores (St)

A store is defined as a surplus after immediate consumption requirements have been met (Swift, 1989), and was used for this research as another positive determinant of sensitivity. The concept of saving – such as the saving of crops – is a factor in the forming of coping-related strategies and measures (Ahamed, 2013; Bormudoi and Nagai, 2017; Hahn et al., 2009). For example, the ability to sell available stored goods (such as cashable goods like jewellery, crops and seeds) to overcome difficulties in a time of crisis is a specific, economic measure of coping capacity. This means that the lower the amount of stored goods in a rural community, the weaker the store-related coping capacity and ability to absorb impacts resulting from exposure. Consequently, the impacts are potentially more severe, meaning that the community is more sensitive to exposure. Note that stores herein do not include money, revealed by financial resources availability in Section 5.2.3 below, to be used to repair the damaged road due to geo-hazards described in Section 5.2.1.

In order to satisfy that the higher level of stores leads to the higher level of sensitivity as revealed in Eq. 5-7, this research adapts a method suggested by Burrow (2014) for the development of a store indicator, St, as stated in Eq. 5-18. Such indicator is to measure food self-sufficiency referring to the ability to satisfy food needs with domestic production (Clapp, 2017).

$$St = \frac{Td}{Max\ Td} \qquad Eq. 5-18$$

where Td is the total number of days in a given year when a rural community is not self-sufficient for food needs, and $Max\ Td$ is the highest number of such days obtained for the considered communities.

5.2.2.3 Claims (Cl)

Claims are used herein as another positive determinant of sensitivity for a community, for the reasons described below. A claim is a type of asset referring to a series of processes that redistribute available resources to provide assistance for others (Swift, 1989). At the simplest level, family and friends can provide support for each other in the form of food, labour, or other resources to help them manage in difficult times. Further, redistributive community taxes are devised to ensure survival of the poor in a crisis. In many rural societies in developing countries, payments or the provision of labour services to a dominant traditional political authority create a social contract under which the political authority is expected to help in a crisis by redistributing food. This system implies that individuals have both an obligation to share resources and a right to require help in case of need. The ability to acquire help in this way is considered to be a social factor in coping, and a positive change in this component, such as lending cash or pawning valuables makes a positive contribution to the overall coping capacity (Bormudoi and Nagai, 2016). Consequently, the more assistances the more community members can obtain, the less the sensitivity.

In order to satisfy that the higher level of claims leads to the higher level of sensitivity as revealed in Eq. 5-7, the claim indicator, Cl, was developed as follows:

$$Cl = \frac{\frac{Tnp}{Tp}}{Max\frac{Tnp}{Tp}} \qquad Eq. 5-19$$

where Tnp is the total number of people who cannot receive assistance in a community when facing difficulty, and $Max\frac{Tnp}{Tp}$ is the highest percentage of people who cannot receive assistance between considered communities.

5.2.3 Resilience (RE)

Following the approach advocated by Turner et al. (2003), resilience in this study was defined as a rural community's capacity to adapt to exposure (see Table 3-4 in Chapter 3 for more cases for adaptation). Resilience describes a system's capacity to bounce back to a reference state following the exposure and to adapt to a series of the fundamentally medium to long term measures to change the system so that it can better cope with the exposure in future. Based on this, resilience in the context of this research was measured in terms of the potential for community members to participate in construction, maintenance and rehabilitation of rural roads (Wattam and IT Transport Ltd, 1998; IT Transport Ltd, 2003; PIARC, 2013). For example, community members could participate in a road project where the original road could be upgraded into climate resilient road. This implied that a community changed itself to adapt to new environment, i.e., the community upgrades road to adapt to possibly frequent geo-hazards.

Such community-participation-based adaptation could help repairing the damaged road and thereby recover access. Community members' participation concerns the capabilities of individuals including the relevant knowledge, skills and expertise to plan, design and build a road (Lusthaus et al., 2002). This study herein considered community members to be labourers (La) (i.e., hard physical workers related to repairing road damaged by geo-hazards), supervisors (Sup) (i.e., people who supervise road repair), technicians (Te) (i.e., people who are good at the detailed technical aspect of road repair) and monitoring (Mon) (i.e., people who examine (a.) quantity and quality of road repair project, and (b.) all documents related to this project) (Department for International Department, 2003).

Consequently, this study assumes that the greater number of community members' participation, the faster the community can repair damaged roads and recover access, and therefore, the greater the community's resilience.

In order to satisfy that the higher level of community participation and resilience, the lower level of vulnerability as revealed in Eq. 4-1 and Eq. 4-5, a community participation indicator, C_p, was developed as follows:

$$RE = \frac{w_{RE} \times \frac{La \times w_{La} + \ Sup \times w_{La} + Te \times w_{La} + Mon \times w_{La}}{Tp}}{MAX\ w_{RE} \times \frac{La \times w_{La} + \ Sup \times w_{La} + Te \times w_{La} + Mon \times w_{La}}{Tp}} \qquad Eq. 5-20$$

Where La is the number of labourers in a community, Sup is the number of supervisors, Te is the number of technicians, and Mon is the number of monitors. w_{La}, w_{Sup}, w_{Te} and w_{mon} are the relative weights of labourers, supervisors, technician and monitors, and $w_{La} + w_{Sup} + w_{Te} + w_{mon} = 1$. $MAX\ w_{RE} \times \frac{La \times w_{La} + Sup \times w_{La} + Te \times w_{La} + Mon \times w_{La}}{Tp}$ is the maximum value of a community for all communities considered.

5.3 Summary

This chapter defined rural community vulnerability to loss of road access provision in terms of vulnerability-determining factors and quantitatively analyse those factors identified. Three components of rural community road access vulnerability were described, namely: exposure, sensitivity, and resilience. Exposure was defined in terms of road condition and disruption to road access. This was decomposed into a three-hierarchical structure: hazardous events, hazardous groups and exposure. Thereafter, the overall exposure of a community was described in mathematical terms by summing the risk level of hazardous groups acquired by summing the risk levels of hazardous events.

Sensitivity was defined to be the community's susceptibility to exposure derived from the inherent characteristics of a rural community (i.e. rural community assets disaggregated into investments, stores, and claims). The overall sensitivity of a community was described in mathematical terms by summing measures of investments, stores and claims. Of which, investments are the sum of human, productive and collective assets where human assets are the aggregation of the total population, taking into account the proportion of women, the elderly, children, the disabled and the female heads of household. Productive assets were determined from the addition of livestock and crops; and collective assets were totality of rural road route value, all season access and rural transport service.

Resilience was defined to be the ability of a rural community to withstand exposure and was represented by the community participation. The community participation was mathematically described as the availability of local resources.

In next chapter, the uncertainties involved in the vulnerability assessment model described in chapter 4 will be addressed.

CHAPTER 6 ADDRESSING UNCERTAINTY

6.1 Introduction

This chapter addresses the uncertainties associated with the vulnerability assessment model described in Chapter 4, i.e., judgement uncertainty related to uncertainty for expert judgement on the estimate of value of parameters considered in Chapter 5; uncertainty related to the pairwise comparison process where parameters' relative weights can be calculated; and aggregation uncertainty related to modelling of a rural community road access vulnerability via its components consisting of exposure, sensitivity and resilience.

Since fuzzy concept related approaches (such as membership function and fuzzy logic) were identified in Chapters 2 and 3 as a suitable tool, for the purposes of this research, for dealing with uncertainty, the estimation of parameter's value can be handled using the linguistic expression/uniform format number (UFN) process described in Section 6.2. Similarly, uncertainty related to the pairwise comparison process is addressed using fuzzy AHP described in Section 6.3. Based on above, a fuzzy calculation procedure with respect to the vulnerability related indicators developed in Chapter 5 is described in Section 6.4.

Vulnerability could be calculated by summing its three determinants (i.e. exposure + sensitivity + resilience) or it could be calculated by multiplying the three determinates (more approaches for vulnerability calculation can be found in Section 3.4 in Chapter 3). To address this aggregation uncertainty, a fuzzy (rule-based) system was established for purpose of evaluating the vulnerability (i.e., the vulnerability evaluation model) and is described in Section 6.5. The vulnerability evaluation model consists of three parts, namely the development of the fuzzy rule base in Section 6.5.1, the mathematical representation of fuzzy rules in Section 6.5.2, and the creation of a fuzzy inference system in Section 6.5.3.

6.2 Judgement uncertainty

For parameters (e.g. the number of populations in a community, see Chapter 5) considered in a vulnerability analysis model, the corresponding precise statistical data is not always available, particularly in rural areas. Therefore, expert opinion might be used to augment and comment on any data collected in the field or from records. However, experts themselves may not be able to provide precise answers and to account for these judgements. To address this, a process based on using a UFN index (see section 4.3 in Chapter 4) was developed to enable an expert to express imprecision or provide approximate information (An et al., 2011). Accordingly, the UFN allows an expert to convey their opinions by either a range of numerical values or a fuzzy number. Table 6-1 outlines the general concept of the approach.

Table 6-1: The UFN's expression of linguistically numerical description

Description	Input values	Input type	UFNs
"… is a"	$\{a\}$	A numerical value	$\{a, a, a, a\}$
"… is between a and b"	$\{a, b\}$	A range of number	$\{a, \frac{a+b}{2}, \frac{a+b}{2}, a\}$
"… is between a and c and most likely to be b"	$\{a, b, c\}$	Triangular fuzzy numbers	$\{a, b, b, c\}$

"… is between a and d and most likely between b and c"	$\{a, b, c, d\}$	Trapezoidal fuzzy numbers (TFNs)	$\{a, b, c, d\}$

6.3 Fuzzy AHP

According to the comparison of several fuzzy AHP approaches in Section 4.3.2 in Chapter 4, the Buckley's fuzzy AHP (1985) was selected to calculate the relative weights of the determinants of the vulnerability analysis model presented in Chapter 5 (see for example Eq. 5-5). The way in which fuzzy AHP was used to achieve this are as follows:

Stage 1: Establishment of a Fuzzy AHP estimation scheme

The first stage is to establish a Fuzzy AHP estimation scheme through which a pairwise comparison can be conducted. For this purpose, the estimation scheme proposed by Chen (2012) was used (see Table 6-2). The estimation scheme is similar to Staay's AHP scheme in using linguistic descriptors to represent the intensity of importance. However, whereas AHP uses crisp numbers to represent the linguistic descriptor, Fuzzy AHP uses fuzzy numbers. For example, "weak importance" is represented by the crisp number 3 in AHP and by the TFN (2,3,3,4) in Fuzzy AHP (see Table 6-2).

Table 6-2 Trapezoidal fuzzy number comparison scheme

Index	Description	TFN
1	Equal importance	(1,1,1,2)
2	Between equal and weak importance	(1,2,2,3)
3	Weak importance	(2,3,3,4)

4	Between weak and strong importance	(3,4,4,5)
5	Strong importance	(4,5,5,6)
6	Between strong and very strong importance	(5,6,6,7)
7	Very strong importance	(6,7,7,8)
8	Between very strong and absolute importance	(7,8,8,9)
9	Absolute importance	(8,9,9,9)

Stage 2: Construction of fuzzy comparison matrix

Following the pairwise comparison process undertaken by participants a fuzzy comparison matrix shown in Eq. 6-1 is created. This is a collection of all judgements each of which represents the preference intensity of one determinant over another. The size of the matrix depends on the number of the determinants to be compared. For example, n determinants result in an $n \times n$ matrix. The fuzzy comparison matrix, M, is defined as (Chen, 2012):

$$M = \begin{bmatrix} m_{1,1} & m_{1,2} & \cdots & m_{1,j} \\ m_{2,1} & m_{2,2} & \cdots & m_{2,j} \\ \vdots & \vdots & \ddots & \vdots \\ m_{i,1} & m_{i,2} & \cdots & m_{i,j} \end{bmatrix} \qquad Eq. 6-1$$

$$m_{i,j} = \{a_{i,j}, b_{i,j}, c_{i,j}, d_{i,j}\} \qquad Eq. 6-2$$

$$m_{i,j} = \frac{1}{m_{j,i}} = \left\{\frac{1}{a_{i,j}}, \frac{1}{b_{i,j}}, \frac{1}{c_{i,j}}, \frac{1}{d_{i,j}}\right\} \qquad Eq. 6-3$$

where any entry $m_{i,j}$ is the relative importance of i^{th} determinant against the j^{th} determinant, $a_{i,j}, b_{i,j}, c_{i,j}$ and $d_{i,j}$ are the members of TFN (such as (a,b,c,d) = (1,1,1,2)).

If $a_{i,j}$, $b_{i,j}$, $c_{i,j}$, $d_{i,j}$ > *1* then the i^{th} determinant is more significant than the j^{th} determinant, if $a_{i,j}$, $b_{i,j}$, $c_{i,j}$, $d_{i,j}$ = *1* then the mth determinant is equal to the n^{th} determinant, if $a_{i,j}$, $b_{i,j}$, $c_{i,j}$, $d_{i,j}$ <*1* then the i^{th} determinant is relatively less important than the j^{th} determinant.

Stage 3: Calculation of fuzzy weights

Using the fuzzy comparison matrix, the weights of the determinants are calculated using the geometric mean technique according to Eq. 6-1 to Eq. 6-3 Buckley, 1985):

$$u_i = \left(\prod_{i=1}^{n} m_{ij}\right)^{1/n}, \forall\ i = 1,2,\ldots,n \qquad Eq. 6-4$$

$$w_i = \frac{u_i}{(u_1 \oplus u_2 \oplus \ldots \oplus u_i \oplus u_n)} \qquad Eq. 6-5$$

in which m_{ij} is the fuzzy preference value of the i^{th} determinate compared to the j^{th} determinant, and u_i is the geometric mean of the fuzzy preference value of the i^{th} determinate compared to the other determinant, and w_i is the fuzzy weight of the i^{th} determinate.

Stage 4: Defuzzification and normalisation

The fuzzy weights are transformed into crisp values using Eq. 6-6 (Bojadziev and Bojacziev 1997). The crisp relative weight w_i of the i^{th} determinant is defined as:

$$w_i' = \frac{a_i + 2(b_i + c_i) + d_i}{6} \qquad Eq. 6-6$$

then, normalised relative weight w_i'' of the i^{th} determinant can be computed by (Chen, 2012):

$$w_i'' = \frac{w_i'}{\sum_{i=1}^{n} w_i'} \qquad Eq. 6-7$$

Stage 5: consideration of experts' competence

When m experts participate in the pairwise comparison process and n experts complete this process, the expert judgements were aggregated using Eq. 6-8 stated below, following the approach suggested by An et al. (2011) was used to aggregate several expert judgements on a parameter value considering expert's competence.

$$ww_i'' = \frac{\sum_{k=1}^{m} w_{i_k}'' EI_k}{\sum_{k=1}^{n} EI_k} \qquad Eq. 6-8$$

Where ww_i'' is the weighted relative weight of the i^{th} determinant, w_{i_k}'' is the judgement of k^{th} expert for the relative weight of the i^{th} determinant, the expert index (EI) of the k_{th} expert is given by EI_k.

According to An et al. (2011), EI can be expressed by:

$$EI_i = \frac{EE_i}{\sum_{j=1}^{n} EE_j} \qquad Eq. 6-9$$

Where EE_i represents the i^{th} expert's experience in relation to vulnerability analysis of rural communities. EE takes a value between 1 to 9 where 1 means that the expert's experience is not very significant and 9 very significant. Note EI should be reviewed when the context alters (For example, expression of the competence of road managers by EI (or $EI_{road\ managers}$) for calculating undesirable road condition and road access loss risks cannot be used for calculating human assets. Instead, EI should be re-reviewed, as $EI_{social\ workers}$, in the light of social works' experience, as social works are supposed to provide relevant data for human assets' calculation).

6.4 Fuzzy calculation

As stated in Chapter 6, exposure, sensitivity and resilience were multi-hierarchical models. For example, the exposure (top layer) was determined by the hazardous group(s) (e.g. agriculture) (middle layer) determined by hazardous event(s) (e.g. the disruption of access to animal grazing) (bottom layer). Therefore, the hazardous event should be initially calculated to obtain the results of the corresponding hazardous group that leads to the result of exposure. Therefore, the calculation of the hazardous event could be a fuzzy calculation if expert opinion is used to provide data. Consequently, the fuzzy calculation is mainly related to indicators presented by Eq. 5-1, Eq. 5-2, Eq. 5-9, Eq. 5-11, Eq. 5-12, and Eq. 5-15 to Eq. 5-20 where the parameters and their weights take the form of TFNs.

6.4.1 Fuzzy number operation

To this end above, TFN operations (i.e., addition, subtraction, multiplication and division) were employed as follows (Lee, 2005):

Given two TFNs $\tilde{A} = (a_1, b_1, c_1, d_1)$ and $\tilde{B} = (a_2, b_2, c_2, d_2)$,

Addition: $\tilde{A} + \tilde{B} = (a_1 + a_2,\ b_1 + b_2, c_1 + c_2, d_1 + d_2)$ $\quad Eq. 6-10$

Subtraction: $\tilde{A} - \tilde{B} = (a_1 - d_2,\ b_1 - c_2, c_1 - b_2, d_1 - a_2)$ $\quad Eq. 6-11$

Multiplication of a TFN by a real number r: $r\tilde{A} = (ra_1, rb_1, rc_1, rd_1)$ $\quad Eq. 6-12$

Multiplication by two TFNs: $\tilde{A}\tilde{B} \cong \{[(b_1 - a_1)\alpha + a_1] \times [(b_2 - a_2)\alpha + a_2], [(d_1 - c_1)\alpha + d_1] \times [(d_2 - c_2)\alpha + d_2]\}$ $\quad Eq. 6-13$

Division: $\frac{\tilde{A}}{\tilde{B}} \cong \left[\frac{(b_1-a_1)\alpha + a_1}{(b_2-a_2)\alpha + a_2}, \frac{(d_1-c_1)\alpha + d_1}{(d_2-c_2)\alpha + d_2}\right]$ $\quad Eq. 6-14$

Where $\alpha = 0$ and $\alpha = 1$ (α is α cut (see Appendix A)).

6.4.2 Fuzzy calculation

When several experts are engaged to give their opinions on parameter's values, their competence was considered to be related with their opinions. Accordingly, when m expert participate in the data collection and n experts provide subjective judgements for the ith parameter, the expert judgements were aggregated using a weighted trapezoidal averaging operator as suggested by An et al. (2011). This is described mathematically by Eq.6-15 (An et al., 2011).

$$A^i = \left(a^i, b^i, c^i, d^i\right) = \left(\frac{\sum_{k=1}^{m} a_k^i EI_k}{\sum_{k=1}^{n} EI_k}, \frac{\sum_{k=1}^{m} b_k^i EI_k}{\sum_{k=1}^{n} EI_k}, \frac{\sum_{k=1}^{m} c_k^i EI_k}{\sum_{k=1}^{n} EI_k}, \frac{\sum_{k=1}^{m} d_k^i EI_k}{\sum_{k=1}^{n} EI_k}\right) \qquad Eq.6-15$$

where A^i stands for the overall judgements of m experts for the ith parameter, a^i, b^i, c^i and d^i are the numbers of UFN A^i, a_k^i, b_k^i, c_k^i and d_k^i are the numbers of UFN A_k^i that represents the judgement of the k^{th} expert for the i^{th} parameter.

As the units of indicators related to the fuzzy calculation above are heterogeneous, each was defuzzfied early using Eq. 6-16 (Bojadziev and Bojadziev, 1997), and was normalised later on by dividing the maximum quantity for all communities considered (see for example Eq. 5-3 and Eq. 5-4).

$$X = \frac{a_i + 2(b_i + c_i) + d_i}{6} \qquad Eq.6-16$$

Where X represents any indicator related to the fuzzy calculation (see Equations mentioned above).

6.5 Aggregation of uncertainty

6.5.1 Development of fuzzy rule base

The development of the fuzzy rule-base aims to create a collection of rules to determine vulnerability via the combination of exposure, sensitivity and resilience. To this end, a fuzzy inference system was developed. First, the form of the fuzzy rule was designed in section 6.5.1.1. Secondly, the derivation of the fuzzy rules is described in section 6.5.1.2. The fuzzy rules generated are reviewed in section 6.5.1.3.

6.5.1.1 Design of fuzzy rule

As stated in Chapter 5, a rural community's road access vulnerability was simultaneously determined by its three components, i.e., exposure to the disruptive road access provision, sensitivity and resilience to such exposure. Therefore, a fuzzy rule representing this relation should be designed in the form of "IF…AND…THEN". The 'IF…AND' part is typically referred to as the antecedent, while the 'THEN' part is referred to as the consequent as (see Chapter 3). For example:

'If (antecedent) exposure is very low AND sensitivity is very low AND resilience is very high, THEN (consequent) vulnerability is very low'.

The logical connective conjunction (i.e., AND) was used, as it can ensure the compound proposition that is true only if individual (or simple) propositions that constitutes that compound proposition are all true. For example, only if *"exposure is very low"* is true, *"sensitivity is very low"* is true, and *"resilience is very high"* is true, *"exposure is very low AND sensitivity is very low, AND resilience is very high"* is true. Thereafter, the logical connective implication (i.e., THEN) was employed to build a bridge between vulnerability and its components. For example, *"exposure is very low AND sensitivity is very low, AND resilience is very high"* that is true implies *"vulnerability is very low*" with a value of true.

Accordingly, the design of the rule provides a basis for vulnerability inference – a process to obtain vulnerability-related knowledge by using existing vulnerability component related knowledge. The antecedent of the rule corresponds to the conditions (i.e. high) of vulnerability components under which a particular chunk of knowledge can be recalled, and the consequent corresponds to the result of utilising that knowledge, which is the condition of vulnerability. This concept is described in more detail in Section 6.5.

Note the above rule is a vague statement because it provides no explicit definition regarding the boundaries of '*very low*' and '*very high*' (see Section 2.3 in Chapter 2). Hence, in fuzzy logic terminology; it is referred to as a fuzzy (or vague) proposition or rule.

6.5.1.2 Derivation of fuzzy rule

6.5.1.2.1 Generation of fuzzy rules

The generation of the fuzzy rules is based on the assumption that the determinants are added together, as suggested by Preston et al. (2009) and is given in Eq. 6-17.

$$Vulnerability = Exposure + Sensitivity + Resilience \qquad Eq. 6-17$$

The significance levels of both exposure and sensitivity were assessed using the Likert scale 1 to 5 (Trochim and Donnelly, 2008) where a score of 1 represents very low exposure, and a score of 5 is very high. For resilience a scale of -1 to -5 was used where a score of -1 represents very low, and -5 is very high. Accordingly, from the above it may be seen that the numerical range of vulnerability scores is determined by two particular combinations of the significance levels of the components of vulnerability. One is that 'If exposure is *very low*, sensitivity is *very low*, and resilience *is very high*, then vulnerability *is very low'*. Another is 'If exposure is *very high*, sensitivity is *very high*, and resilience is *very low*, then vulnerability is *very high'*. From Eq. 6-17, it can be seen that the range of vulnerability is therefore confined to the interval [-3, 9]. The range of possible vulnerability values was evenly divided into five intervals, and each of them represents a numerical range of a specific significance level of vulnerability as demonstrated in Figure 6-1.

As every vulnerability value calculated by Eq. 6-17 can identify which level it belongs to, five rule matrices were developed as shown in Table 6-3. Each matrix consists of 25 elements via a specific significance level of resilience, and each entry can be considered as a rule. For example, the entry (5, 5) in the matrix for resilience = very low and is expressed as follows:

'If exposure is *very low and* sensitivity is *very high* and resilience is *very low*, then vulnerability is *very high'*.

As a result, the fuzzy rule base for this model consists of 125 rules (i.e., five matrices each with 25 possible combinations).

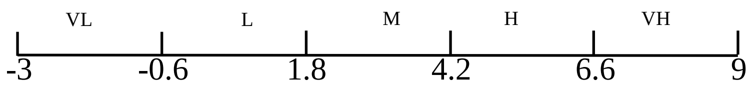


Figure 6-1: Numerical classification of vulnerability

6.5.1.3 Review of fuzzy rules generated

The fuzzy rules generated satisfy the three criteria suggested in the literature when developing a fuzzy rule base (Lee, 1990, Sii et al., 2001 and An et al., 2006). Namely:

- Completeness: The developed collection of the fuzzy rules is complete as at least one rule exists for any input values (i.e. the significance level) of vulnerability components.
- Consistency: The collection of the fuzzy rules is consistent as no rules have the same antecedent part but rather have different consequent parts.
- Continuity: The collection of the fuzzy rules has continuity as no neighbouring rules with consequent part membership functions have an empty intersection.

Table 6-3: Fuzzy rule base matrices

The significance level of resilience = very low

Sensitivity \ Exposure	VH	H	M	L	VL
VH	VH	VH	VH	H	H
H	VH	VH	H	H	H
M	VH	H	H	M	M
L	H	H	M	M	M
VL	H	M	M	M	L

The significance level of resilience = low

Sensitivity \ Exposure	VH	H	M	L	VL
VH	VH	VH	VH	H	M
H	VH	H	M	M	M
M	H	H	M	M	M
L	H	M	M	M	L
VL	M	M	M	L	L

The significance level of resilience = moderate

Sensitivity \ Exposure	VH	H	M	L	VL
VH	VH	H	H	M	M
H	H	H	M	M	M
M	H	M	M	M	L
L	M	M	M	L	L
VL	M	M	L	L	VL

The significance level of resilience = high

Sensitivity \ Exposure	VH	H	M	L	VL
VH	H	H	M	M	M
H	H	M	M	M	L
M	M	M	M	L	L
L	M	M	L	L	VL
VL	M	L	L	VL	VL

The significance level of resilience = very high

Sensitivity \ Exposure	VH	H	M	L	VL
VH	H	H	M	M	L
H	M	M	M	L	L
M	M	M	L	L	VL
L	M	L	L	VL	VL
VL	L	L	VL	VL	VL

VH: Very high;
H: High;
M: Moderate;
L: Low;
VL: Very low.

6.5.2 Mathematical representation of fuzzy rule

The mathematical representation of fuzzy rules refers to the development of membership functions to express vague information (e.g. very low) of the fuzzy rule. The fuzzy inference system operates on a fuzzy rule base where each rule is characterised by the membership function.

This section first describes the universe of discourse for membership functions in Section 6.5.2.1. Secondly, an appropriate shape of membership function is determined in Section 6.5.2.2. Thirdly, a membership function is developed to express specific predicate (see Section 3.4.1 in Chapter 3) in fuzzy rule in Section 6.5.2.3.

6.5.2.1 Determination of universe of discourse

In general, the universe of discourse refers to all available information on a given problem (Bojadziev and Bojadziev, 2007). Since exposure, U, sensitivity, V, resilience, W, and vulnerability X range over 0 and 1 as stated in the vulnerability analysis model in Chapter 6, this range is considered to be the universe of discourse of U, V, W and X where their corresponding significance levels can be mathematically represented through a membership function that has developed and is described below.

6.5.2.2 Determination of membership function shape

From the literature there are three types of commonly used membership function, namely triangular, trapezoidal and Gaussian. As stated in Chapter 4, the trapezoidal membership function has been shown to be particularly suitable for practical applications and therefore it was chosen to express exposure, sensitivity, resilience and vulnerability (see Figure 6-2).

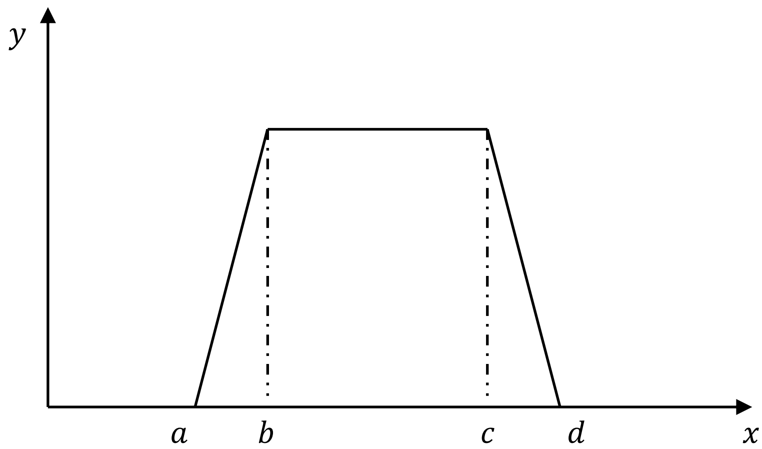


Figure 6-2: Trapezoidal membership function

6.5.2.3 Development of membership function

The inductive reasoning approach was utilised to develop the membership function for the significance levels of both vulnerability and its three components, since other approaches suggested in the literature (e.g. neural networks and genetic algorithms) are less intuitive (and therefore less transparent) and computationally much more expensive than inductive reasoning approach (Ross, 2005). The inductive reasoning approach takes advantage of Shannon's entropy minimisation analysis to determine the thresholds between membership functions (Christensen, 1981).

According to Shannon (1948), entropy refers to the amount of information conveyed by a message and the more information the message conveys, the more uncertainty the message has. For example, the message “the sun rises in the east and sets in the west” is an absolutely certain, thus, it does not convey too much information. Using the approach suggested by Shannon (1948), entropy (or the amount of information) was measured by the summation of probability multiplied by the logarithm of the probability for all outcomes of a trial where one and only one outcome is true (or can occur). Mathematically, the entropy, H, was measured as follows:

$$H = -k \sum_{i=1}^{n} p_i \times \log p_i \qquad Eq. 6-18$$

where k is a positive constant, p_i is the probability of event i, and $-\log p_i$ (or $\log \frac{1}{p_i}$) is the amount of information generated by the occurrence of event i.

Therefore, the higher the probability of the occurrence of a particular outcome, the less amount of information it reveals, the lower the entropy and thus the lower the uncertainty level, and vice versa. Based on this, the entropy minimisation analysis seeks to determine the point with minimum of entropy in an interval as the threshold point for the classification of the membership function.

6.5.2.3.1 Membership function generation

In order to classify a membership function such that it can express five levels of significance for vulnerability components and vulnerability, a process described by Christensen (1981) and Ross (2005) was used. Using this process, the classification process starts by segmenting the membership into two classes. Thereafter, the two classes were partitioned into three classes, which are further separated into five classes.

Specifically, the first segmentation begins with the generation and classification of samples in the range of between x_1 and x_2 (the range represents the universe of discourse for exposure, sensitivity, resilience and vulnerability respectively). A selected sample x was divided into p and q regions, as is demonstrated in Figure 6-3. The entropy of x, within the interval [x_1, x_2], was calculated, and the x with the minimum entropy was considered from the above to be the primary threshold value (PRI). PRI was used to separate the region [x_1, x_2] into two, as shown in Figure 6-4 (a). Mathematically, the entropy of x in the region x_1 and x_2 was calculated using Eq. 6-19 to Eq. 6-25 (Christensen, 1981):

$$S(x) = p(x) \times S_p(x) + q(x) \times S_q(x) \qquad Eq. 6-19$$

where

$$S_p(x) = -[p_1(x) \times lnp_1(x) + p_2(x) \times lnp_2(x)] \qquad Eq. 6-20$$

$$S_q(x) = -[q_1(x) \times lnq_1(x) + q_2(x) \times lnq_2(x)] \qquad Eq. 6-21$$

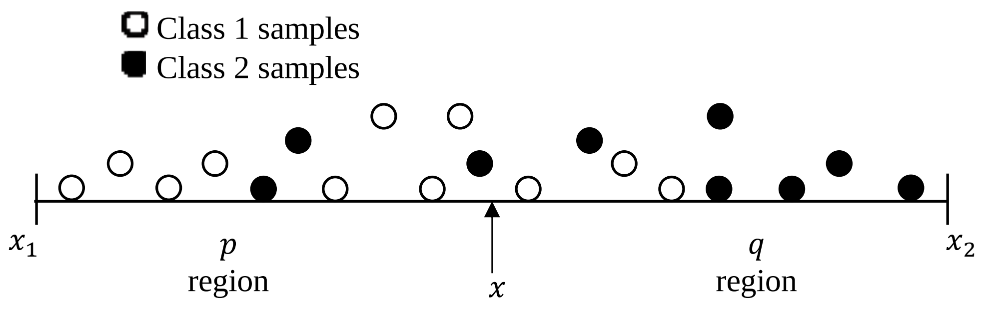


Figure 6-3: Threshold value idea (Source: Ross, 2005)

where $p_k(x)$ and $q_k(x)$ = conditional probabilities that the class k sample is in the region $[x_1, x_1 + x]$ and $[x_1$+x, $x_2]$;

$p(x)$ and $q(x)$ = probabilities that all samples are in the region $[x_1, x_1 + x]$ and $[x_1 + x, x_2]$;

$p(x) + q(x) = 1$

$$p_k(x) = \frac{n_k(x) + 1}{n(x) + 1} \qquad Eq. 6-22$$

$$q_k(x) = \frac{N_k(x) + 1}{N(x) + 1} \qquad Eq. 6-23$$

$$p(x) = \frac{n(x)}{n} \qquad Eq. 6-24$$

$$q(x) = 1 - p(x) \qquad Eq. 6-25$$

where $n_k(x)$ is the number of class k samples in $[x_l, x_l + x]$

$n(x)$ is the total number of samples in $[x_l, x_l + x]$

$N_k(x)$ is the number of class k samples in $[x_l + x , x_2]$

$N(x)$ is the total number of samples in $[x_l + x , x_2]$

n is the total number of samples in $[x_1, x_2]$

l is a general length along the interval $[x_1, x_2]$

Following the first segmentation, the second segmentation on each of regions, shown schematically in Figure 6-4 (a), was carried out in order to locate the secondary threshold values (SEC). By using the Eq. 6-19 to Eq. 6-25, SEC1 and SEC2 are obtained. Hence, PRI, SEC1 and SEC2 together partition the range into three parts, as shown in Figure 6-4 (b). Thereafter, the third segmentation on each of regions shown in Figure 6-4 (b) was undertaken so as to determine the tertiary threshold values (TER). TRE1, TRE2, TRE3 and TRE4 utilising Eq. 6-19 to Eq. 6-25. As a result, PRI, SEC1, SEC2, TRE1, TRE2, TRE3 and TRE4 were used to separate the interval $[x_1, x_2]$ into five classes, as shown in Figure 6-4 (c).

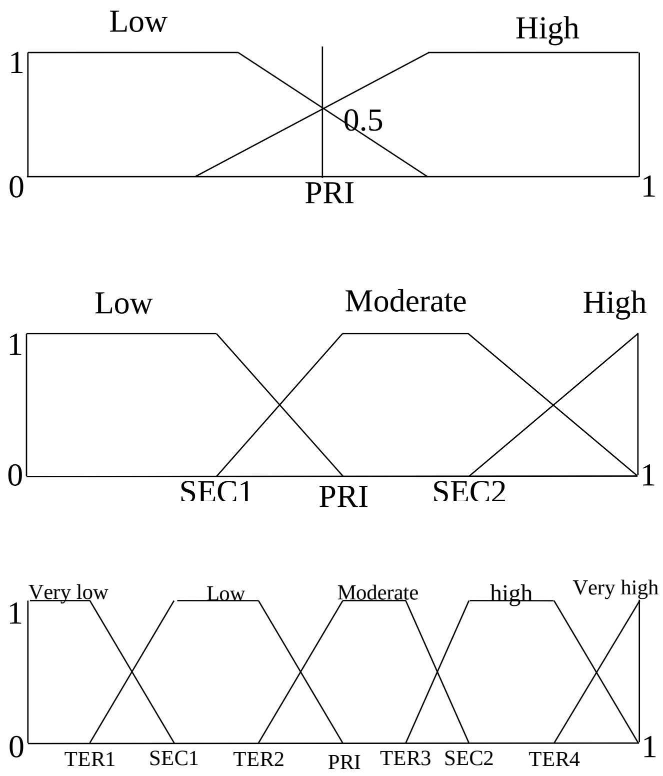


Figure 6-4: Segmentation: (a) the first segmentation, (b) the second segmentation, (c) the third segmentation (Source: adapted by Ross (2005))

a. The membership function generation for exposure

As stated above, the development of the membership functions for exposure begins with the generation and classification of samples x. As the universe of discourse for exposure, U, is in the range of [0,1], the samples were arbitrarily produced and classified as shown in Table 6-4.

Table 6-4: Segmentation of x into two arbitrary classes (based on universe of discourse for exposure)

x	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Class	1	1	1	1	2	1	1	2	2	2	2

Following the above, the mid-value between any two adjacent values can be selected to be the value of x. Eq. 6-19 to Eq. 6-25 were employed to calculate p_1, p_2, q_1, q_2, $p(x)$, $q(x)$, $S_p(x)$, $S_q(x)$ and S for each of value of x selected, as shown in Table 6-5. The value of x that holds the minimum value of entropy (S) was chosen as the PRI. As a result, x = 0.65 was determined to be the PRI. This locates the boundaries between the membership functions of "*low*" and "*high*" as shown in Figure 6-5 (a).

The same procedure as illustrated in Table 6-5 was repeated for the low and high partitions for different values of x. This leads to, $x = 0.42$ (i.e., SEC1) for the lower bound partition and $x = 0.88$ for the upper bound partition (i.e., SEC2). Therefore, PRI, SEC1 and SEC2 simultaneously locate the boundaries among the membership functions of "*low*", "*moderate*" and "*high*" as shown in Figure 6-5 (b).

Table 6-5: Computations for selection of threshold point PRI

x	**0.35**	**0.45**	**0.55**	**0.65**
p_1	$\frac{4+1}{4+1} = 1$	$\frac{4+1}{5+1} = \frac{5}{6}$	$\frac{5+1}{6+1} = \frac{6}{7}$	$\frac{6+1}{7+1} = \frac{7}{8}$

p_2	$\frac{0+1}{4+1} = \frac{1}{5}$	$\frac{1+1}{5+1} = \frac{1}{3}$	$\frac{1+1}{6+1} = \frac{2}{7}$	$\frac{1+1}{7+1} = \frac{1}{4}$
q_1	$\frac{2+1}{7+1} = \frac{3}{8}$	$\frac{2+1}{6+1} = \frac{3}{7}$	$\frac{1+1}{5+1} = \frac{1}{3}$	$\frac{0+1}{4+1} = \frac{1}{5}$
q_2	$\frac{5+1}{7+1} = \frac{3}{4}$	$\frac{4+1}{6+1} = \frac{5}{7}$	$\frac{4+1}{5+1} = \frac{5}{6}$	$\frac{4+1}{4+1} = 1$
$p(x)$	$\frac{4}{11}$	$\frac{5}{11}$	$\frac{6}{11}$	$\frac{7}{11}$
$q(x)$	$\frac{7}{11}$	$\frac{6}{11}$	$\frac{5}{11}$	$\frac{4}{11}$
$S_p(x)$	0.32	0.518	0.49	0.463
$S_q(x)$	0.58	0.603	0.518	0.321
S	0.4854	0.564	0.502	0.411

Thereafter, the procedure above was carried out on each of the intervals [0,0.42], [0.42, 0.65], [0.65, 0.88] and [0.88,1] for the diverse values of x as shown in Figure 6-5 (b). Consequently, $x = 0.27$ with minimum value of entropy (S) in the interval [0, 0.42], $x = 0.57$ with minimum value of entropy (S) in the interval [0.42, 0.65], $x = 0.80$ with minimum value of entropy (S) in the interval [0.65, 0.88] and $x = 0.96$ with minimum value of entropy (S) in the interval [0.88, 1.0] were identified to be the TER1, TER2, TER3 and TER4 for the third partition as illustrated in Figure 6-5 (c).

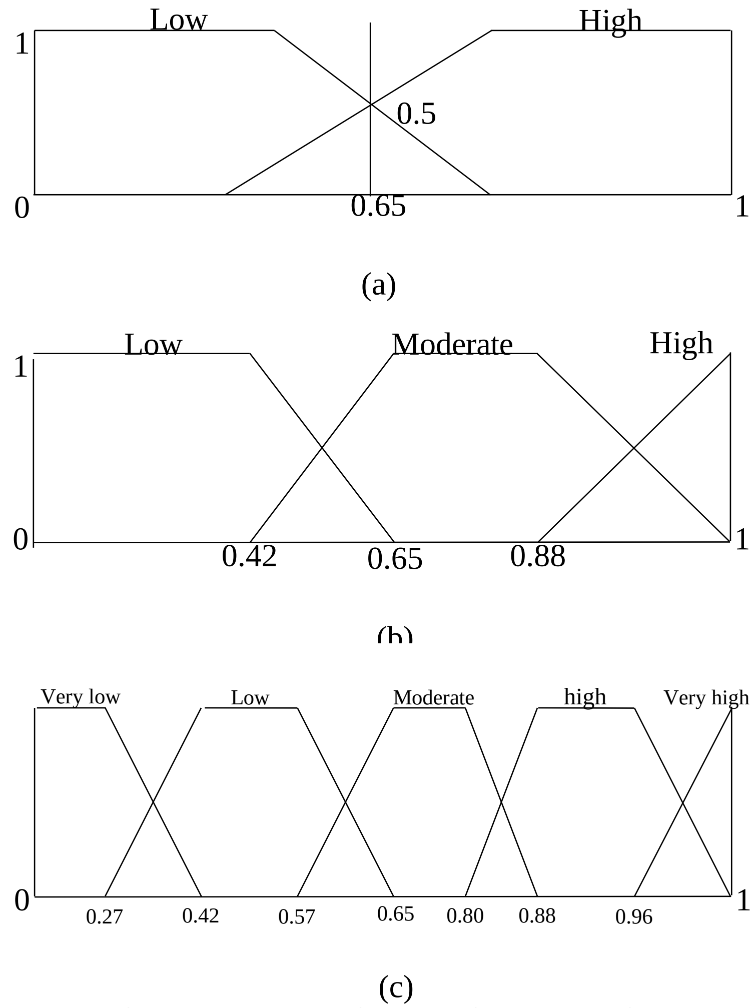


Figure 6-5: Development of the membership function for the significance level of exposure: (a) first partition; (b) second partition; (c) third partition

The developed membership functions, shown in Figure 6-5 (c), can also be represented as:

$$\mu_{very\ low}^{exposure}(x) = \begin{cases} 1, & 0 \le \text{and} x \le 0.27 \\ \dfrac{20 \times (0.42 - x)}{3}, & 0.27 \le \text{and} x \le 0.42 \\ 0, & x \ge 0.42 \end{cases} \qquad Eq. 6-26$$

$$\mu_{low}^{exposure}(x) = \begin{cases} 0, & and x \le 0.27 \\ \dfrac{20 \times (x - 0.27)}{3}, & 0.27 \le \text{and} x \le 0.42 \\ 1, & 0.42 \le \text{and} x \le 0.57 \\ \dfrac{25 \times (0.65 - x)}{2}, & 0.57 \le x \le 0.65 \\ 0, & x \ge 0 \end{cases} \qquad Eq. 6-27$$

$$\mu_{moderate}^{exposure}(x) = \begin{cases} 0, & and x \le 0.57 \\ \frac{25 \times (x - 0.57)}{2}, & 0.57 \le \text{and} x \le 0.65 \\ 1, & 0.65 \le \text{and} x \le 0.80 \\ \frac{25 \times (0.88 - x)}{2}, & 0.80 \le x \le 0.88 \\ 0, & x \ge 0.88 \end{cases} \quad Eq. 6 - 28$$

$$\mu_{high}^{exposure}(x) = \begin{cases} 0, & and x \le 0.80 \\ \frac{25 \times (x - 0.80)}{2}, & 0.80 \le \text{and} x \le 0.88 \\ 1, & 0.88 \le \text{and} x \le 0.96 \\ 25 \times (1.0 - x), & 0.96 \le x \le 1.0 \\ 0, & x \ge 1.0 \end{cases} \quad Eq. 6 - 29$$

$$\mu_{very\,high}^{exposure}(x) = \begin{cases} 0, & \text{and} x \le 0.96 \\ 25 \times (x - 0.96), & 0.96 \le \text{and} x \le 1.0 \end{cases} \quad Eq. 6 - 30$$

b. *The membership function generation for sensitivity, resilience and vulnerability*

As the generation and classification of the samples x are the same as shown in Table 6-4, the membership functions for the significance levels of sensitivity, resilience and vulnerability, given by Eq. 6-26 to Eq. 6-30 are relevant (cf. Figure 6-5 (c)). Consequently,

$$\mu_{very\,low}^{exposure}(x) = \mu_{very\,low}^{sensitivity}(x) = \mu_{very\,low}^{resilience}(x) = \mu_{very\,low}^{vulnerability}(x) \quad Eq. 6 - 31$$

$$\mu_{low}^{exposure}(x) = \mu_{low}^{sensitivity}(x) = \mu_{low}^{resilience}(x) = \mu_{low}^{vulnerability}(x) \quad Eq. 6 - 32$$

$$\mu_{moderate}^{exposure}(x) = \mu_{moderate}^{sensitivity}(x) = \mu_{moderate}^{resilience}(x) = \mu_{moderate}^{vulnerability}(x) \quad Eq. 6 - 33$$

$$\mu_{high}^{exposure}(x) = \mu_{high}^{sensitivity}(x) = \mu_{high}^{resilience}(x) = \mu_{high}^{vulnerability}(x) \quad Eq. 6 - 34$$

$$\mu_{very\,high}^{exposure}(x) = \mu_{very\,high}^{sensitivity}(x) = \mu_{very\,high}^{resilience}(x) = \mu_{very\,high}^{vulnerability}(x) \quad Eq. 6 - 35$$

6.5.3 Fuzzy inference system

A fuzzy inference system consisting of a fuzzification process, an inference engine and a defuzzification process working with a fuzzy rule base was developed (Ross, 2005). The operation of this system is summarised in Figure 6-6. Firstly, this system was used to transform the inputs of exposure, sensitivity and resilience into a fuzzy format. Second, the fuzzified inputs were compared to the fuzzy rule base to check which rule's antecedent absolutely match the fuzzified inputs. Those rules that have absolute matching were activated. Third, inference engine assists inferring relevant conclusions through the activated rules. Fourth, the conclusions are transformed into non-fuzzified results via the defuzzification process.

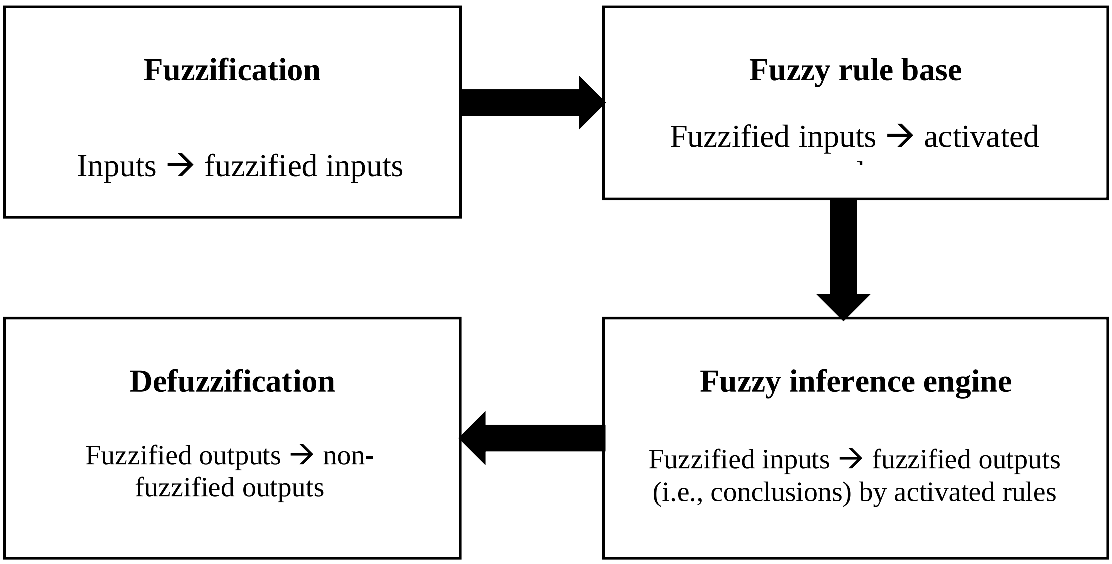


Figure 6-6: Operational process of fuzzy inference system

6.5.3.1 Fuzzification

Fuzzification is typically the process of making an exact number (Zimmermann, 2010) fuzzy. The purpose of fuzzification is to activate the fuzzy rule(s) related to those numbers in the fuzzy rule base (Mendel, 1995; Ross, 2005). For precise numerical values of exposure, sensitivity and resilience generated in Section 6.4, fuzzification aims to convert them into the membership functions that express the significance levels of exposure, sensitivity and resilience.

The conversion above enables quantities of exposure, sensitivity and resilience to recognise the specific significance level(s) they belong to and the degree to which quantities belong to the significance level(s). This degree is also referred to as a membership value and is demonstrated in Figure 6-7. In this regard, the significance level(s) of exposure, sensitivity and resilience recognised (i.e. combinations of the significance levels) were used to determine fuzzy rule(s), including such combinations in the fuzzy rule base. The activated rule(s) were thereafter used for the inference of the vulnerability in a fuzzy inference system as described in Section 6.5.3.2.

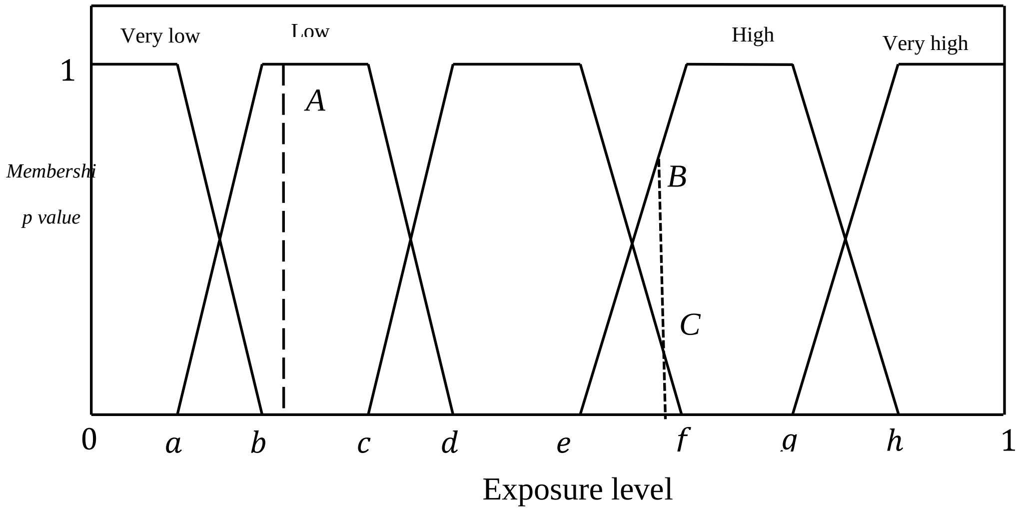


Figure 6-7: Fuzzification process

6.5.3.2 Fuzzy inference engine

Following the activation of fuzzy rule(s) by fuzzifying the input data as described above, activated fuzzy rule(s) was/were used to infer vulnerability quantitatively. This process is summarised in Figure 6-8. Firstly, the Mamdani's minimum logical operator (see Section 4.3 in Chapter 4) was used to propagate the minimum of the three membership values of exposure, sensitivity and resilience to vulnerability, which were derived from the fuzzification stage (Mamdani, 1975). Secondly, the activated rules were combined after truncations if more than one was triggered. The truncated areas of the membership function of vulnerability for the rules were aggregated, enabling the determination of the overall consequent from the individual consequents in the rules activated.

a. Input data are singleton

As the results of exposure, sensitivity and resilience (i.e., the input data for fuzzy inference engine) are exact numbers (see Eq. 5-6, Eq. 5-7 and Eq. 5-20), the approach suggested by Lee (1995) was used to mathematically express the inference process as follows:

The i^{th} rule was defined as:

R_i: if exposure is A_i and sensitivity is B_i and resilience is C_i, then vulnerability is D_i, $i = [1,125]$

where exposure (i.e. e) is the input data of exposure, e ∈ U, sensitivity (s) is the input data of sensitivity, s ∈ V, resilience (re) is the input data of resilience, re ∈ W, vulnerability (v) is the numerical value range of D_i, v ∈ X and A_i, B_i, C_i and D_i respectively represent a specific significance level of exposure, sensitivity, resilience and vulnerability in i^{th} rule, characterised by membership functions μ_{A_i}, μ_{B_i}, μ_{C_i} and μ_{D_i} (μ_{A_i} could be $\mu_{very\ low}^{exposure}(x)$, $\mu_{low}^{exposure}(x)$, $\mu_{moderate}^{exposure}(x)$, $\mu_{high}^{exposure}(x)$ or $\mu_{very\ high}^{exposure}(x)$; μ_{B_i} could be $\mu_{very\ low}^{sensitivity}(x)$, $\mu_{low}^{sensitivity}(x)$, $\mu_{moderate}^{sensitivity}(x)$, $\mu_{high}^{sensitivity}(x)$ or $\mu_{very\ high}^{sensitivity}(x)$; μ_{C_i} could be $\mu_{very\ low}^{resilience}(x)$, $\mu_{low}^{resilience}(x)$, $\mu_{moderate}^{resilience}(x)$, $\mu_{high}^{resilience}(x)$ or $\mu_{very\ high}^{resilience}(x)$; and μ_{D_i} could be $\mu_{very\ low}^{vulnerability}(x)$, $\mu_{low}^{vulnerability}(x)$, $\mu_{moderate}^{vulnerability}(x)$, $\mu_{high}^{vulnerability}(x)$ or $\mu_{very\ high}^{vulnerability}(x)$).

As such, given input data that are exact numbers $e = e_1$, $s = s_1$ and $re = re_1$, the i^{th} rule defined as $R_i: (A_i \ and \ B_i \ and \ C_i) \rightarrow D_i$ can be further expressed as:

$$R_i: \mu_{A_i}(e_1) \ and \ \mu_{B_i}(s_1) \ and \ \mu_{C_i}(re_1) \ \rightarrow \ \mu_{D_i}(v) \qquad Eq. 6-36$$

Since the Mamdani method employs the minimum operation (∧) for the fuzzy implication (→), the above equation can be reformulated as:

$$\mu_{A_i}(e_1)\ and\ \mu_{B_i}(s_1)\ and\ \mu_{C_i}(re_1) = \mu_{A_i}(e_1) \wedge \mu_{B_i}(s_1) \wedge \mu_{C_i}(re_1) = \alpha_i \qquad Eq.6-37$$

where α_i represents the fire strength or matching degree of the i^{th} rule.

As a result, the truncated membership function $\mu_{D_i'}(v)$ of vulnerability for the i^{th} rule was obtained using $Eq.6-38$.

$$\mu_{D_i'}(v) = \alpha_i \wedge \mu_{D_i}(v) \qquad Eq.6-38$$

If there is more than one rule activated (e.g., the i^{th} and j^{th} rules were activated), then the truncated membership function $\mu_{D_i'}(v)$ of the vulnerability for the i^{th} and j^{th} rules can be obtained by:

$$\mu_{D'}(v) = \mu_{D_i'}(v) \vee \mu_{D_j'}(v) \qquad Eq.7-39$$

where ∨ refers to maximum operation.

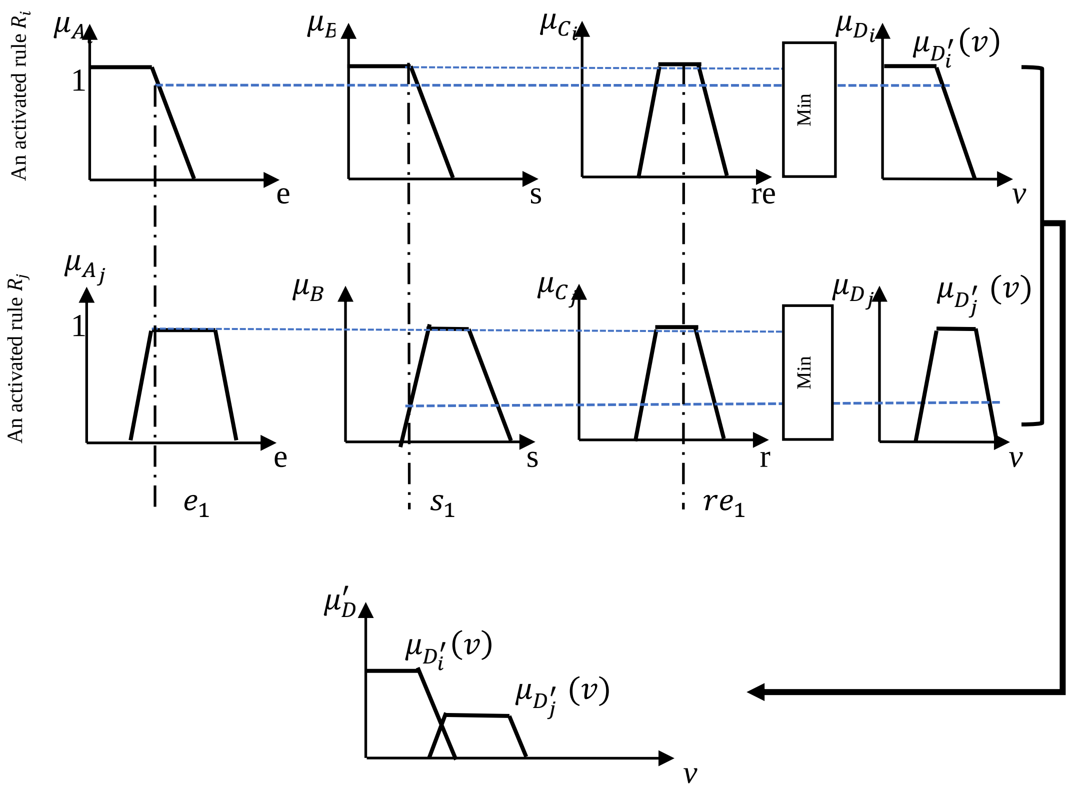


Figure 6-8: Graphical representation of vulnerability inference with singleton input

6.5.3.3 Defuzzification

As the output of the inference process described above was still fuzzy, defuzzification is needed to obtain a crisp value of vulnerability. The centre of area method was used for defuzzification (Lee, 2005; An et al., 2006).

$$z_0 = \frac{\sum_{i=1}^{m} \mu_{D'}(v_i) \times v_i}{\sum_{i=1}^{m} \mu_{D'}(v_i)} \qquad Eq. 6-40$$

where m is the number of quantisation levels of the conclusion membership function.

The centre area method was chosen because it is faster for utilisation due to simple operation (Saletic et al., 2002).

6.6 Summary

This chapter built on the vulnerability assessment model described in Chapter 4 to take into account a number of uncertainties using fuzzy concept related approaches. Firstly, the UFN was developed to express parameter uncertainty. Second, a fuzzy AHP approach proposed to calculate the relative weights of parameters. Third, the exact numerical values of exposure, sensitivity and resilience were calculated using fuzzy calculation. Fourth, a fuzzy system-based vulnerability evaluation model was developed. Through the calculated values of exposure, sensitivity and resilience the developed model can infer vulnerability in both qualitative and quantitative ways.

The following chapter provides a case study to demonstrate the approach to assessing the vulnerability of rural communities to the lack of access provision. The case study will show how the vulnerability identification and analysis processes described in Chapter 5, and the vulnerability evaluation approach outlined in this chapter can be combined to this end.

CHAPTER 7 CASE STUDY

7.1 Introduction

This chapter illustrates the utilisation of the fuzzy concept related vulnerability assessment model developed in Chapters 5 and 6 by a case study. Firstly, the context of case study, i.e., Ganyan, Xiniu, Xiawu and Shuiying villages, Changchunpu district, Guizhou province, China, is described in Section 7.2. Secondly, the data providers and data collection procedures are described in Section 7.3. Based on the data collected the identified determinants of vulnerability to loss of road access provision are presented in Section 7.4 and are quantitatively analysed for the four candidate villages in Section 7.5. The vulnerability of the four villages is evaluated in Section 7.6.

7.2 Study area

The study area was focused on four villages (consisting of Ganyan, Xiniu, Xiawu and Shuiying villages) in Changchunpu District, Bijie City, Guizhou Province, China. They were chosen, since each village is only served by a single road leading to district centre, and their social and economic activities heavily rely on traveling and transporting to/from the district centre. Ganyan, Xiniu, Xiawu and Shuiying villages respectively have a 4-km, 3.4-km, 3.9-km and 5.7-km-long bituminous roads from the village itself to the district centre. Therefore, rural transport services always play a vital role in their livelihood activities. However, as four villages are located in mountainous areas, climate induced geo-hazards impact road access provision especially during the wet season, so that village members have been encountering disrupted access to the district centre.

7.3 Data collection

This section describes (a.) the data providers and (b.) the procedure for collecting data. With respect to data providers, 21 participants agreed to provide the data needed in this case study. They include 3 rural road managers, 16 social workers and 2 road subject related academics. The data they provided is described in Sections 7.4 and 7.5.

The approach for data collection in this case study was by means of individual interviews together with structured questionnaire as described in Chapter 4. As suggested by Ayyub (2001) the following took place:

1. Familiarisation of data providers: the background materials, consisting of the objectives of the research, description of the issues related to rural community road access vulnerability, lists of questions were sent to 21 participants one week in advance of the meeting for elicitation of their opinions on issues. This was done to give them adequate time to become familiar with the vulnerability issues.
2. Training for data providers: Firstly, a presentation/ introduction of background material was carried out at beginning of the interview for purpose of building rapport with interviewees. Second, a trial was performed to see whether or not the interviewees were comfortable with the meaning questions. During this training, all questions remained flexible to enable the wording to be refined or the way questions were asked in the light of interviewees' feedback. For example, an expert might feel uncomfortable to answer the question of likelihood of loss of access provision for a community, but rather answer about the number of days in a given year a community loses its access provision.

3. Collection of data providers' opinions: Once the interviewees were familiar with the research background and feel comfortable to answer questions, a collection of revised questions was established and used to collect their opinions during the interviews.

7.4 Vulnerability identification

Vulnerability identification herein particularly refers to exposure identification (i.e., the identification of risk events resulting from loss of road access provision). It sequentially includes (a.) the confirmation of risk events identified in Chapter 5, (b.) the addition of newly identified risk events, (c.) the confirmation of added risk events for the Ganyan, Xiniu, Xiawu and Shuiying villages.

7.4.1 Vulnerability identification via rural road managers

In this case study, 3 locally experienced rural road managers participated in vulnerability identification. Firstly, the risk events, described in Chapter 5, were only considered further they were confirmed by at least 2 road managers (see Table 7-1and Table 7-2).

Table 7-1: The confirmation of risk events by expert opinion

	Risk category	**Risk ID**	**Identified risk**	**The number of experts aggreging /total number of questioned experts**
Road access loss risk	Education	EH_3^{RAL}	The disruption of access to schools	3/3
		EH_5^{RAL}	The disruption of health educator's visiting	3/3
	Employment	EH_{10}^{RAL}	The disruption of access to perform the traditional marriage	3/3
		EH_{11}^{RAL}	The disruption of access to perform the traditional funeral	2/3

		EH_{12}^{RAL}	The disruption of potential opportunities to be employed	3/3
	Health	EH_{13}^{RAL}	The disruption of access to health centres	3/3
		EH_{14}^{RAL}	The disruption of access to maternity centres	3/3
		EH_{16}^{RAL}	The disruption of undertaking immunisation programs	3/3
	Income and consumption	EH_{17}^{RAL}	Lessen the selling and buying capacities	3/3
		EH_{20}^{RAL}	The negative impact on the standard of living	3/3
	Marketing	EH_{21}^{RAL}	The disruption of access to trading centres	3/3
		EH_{24}^{RAL}	Loss of potential trading opportunities	2/3

Table 7-2: Newly added risk events by road managers

	Risk category	Risk event	Risk description	Risk impact
Road access loss risk	Agriculture	The transportation of tobacco leaf	The tobacco leaf cannot be transported to tobacco station in district centre at the appropriate time	The impact on tobacco farmers
		The transportation of water/fertilizer for irrigation/fertilization	Decrease in transportation of the water/fertilizer for crop irrigation/fertilization	The impact on crop farmers
		The transportation of grass for feeding animals (e.g. pigs)	Decrease in transportation of the grass to rear animals	The impact on pastoralists
		The extension worker's visit	Decrease in visit of extension worker to the village	The impact on farmers/pastoralists
	Education	Labour training	Labours (i.e., villagers) are unable to travel to the place where the skill training is undertaken (e.g. cooking skill)	The impact on labours who want to attend this course
	Employment	Employee attendance	Villagers who have jobs in district centre are unable to travel to district centre	The impact on villagers who have a job in district centre
	Health	Buying medication	The operators of mobile pharmacy do not have road access to the village	The impact on villagers who have demand on medication
		Emergency service	Emergency service does not have road access to the village	The impact on the villagers who need emergency service

	Income and consumption	Buying poultry (e.g. chicken)	Poultry sellers do not have road access to the village	The impact on villagers have demand on poultry
		Acquisition of photo service	The operators of mobile photo studio do not have road access to the village	The impact on villagers who have demand on photo service
		Buying coals	Coal sellers do not have road access to village	The impact on villagers who have demand on coals
		Buying foods and other things used in home	The operators of mobile grocery store do not have road access to the village	The impact on villagers in the village who have demand on foods and others in the grocery
		Transport of material for house construction (e.g. brick, sand, rock)	The villagers are unable to obtain construction material	The impact on villagers who have demand on house construction

7.4.2 Vulnerability identification after consultation with rural road managers

The risk events presented in Tables 7-1 and 7-2 are presented together in Table 7-3 for further analysis described in Section 7.5.

Table 7-3: Risk events related to road access loss risk

	Risk category	**Identified risk**	**Source**
Road access loss risk	Agriculture	The transportation of tobacco leaf	Expert opinion
		The transportation of water/fertilizer for irrigation/fertilization	Expert opinion
		The transportation of grass for feeding animals (e.g. pigs)	Expert opinion
		The extension worker's visit	Expert opinion
	Education	Labour training	Expert opinion
		The access to schools	(Odoki et al., 2008)
		The health educator's visiting	(Odoki et al., 2008)
	Employment	Employee attendance	Expert opinion
		The access to perform the traditional marriage	(Odoki et al., 2008)
		The access to perform the traditional funeral	(Odoki et al., 2008)
		The potential opportunities to be employed	(Odoki et al., 2008)
	Health	Buying medication	Expert opinion
		Emergency service	Expert opinion
		The access to health centres	(Odoki et al., 2008)

		The access to maternity centres	(Odoki et al., 2008)
		The immunisation programs	(Odoki et al., 2008)
	Income and consumption	Buying poultry (e.g. chicken)	Expert opinion
		Acquisition of photo service	Expert opinion
		Buying coals	Expert opinion
		Buying foods and other things used in home	Expert opinion
		Transport of material for house construction (e.g. brick, sand, rock)	Expert opinion
		The selling and buying capacities	(Odoki et al., 2008)
		The standard of living	(Odoki et al., 2008)
	Marketing	The access to trading centres	(Odoki et al., 2008)
		Potential trading opportunities	(Odoki et al., 2008)

7.5 Vulnerability analysis

Vulnerability analysis considers exposure, sensitivity and resilience (see Section 5.2 in Chapter 5). Each component of vulnerability was analysed (a.) using the vulnerability model described in Chapter 5 (Eq. 5-2 and Eq. 5-4 – Eq. 5-6 for exposure, Eq. 5-7 – 5-19 for sensitivity, and Eq. 5-20 and Eq. 5-21 for resilience) and (b.) addressing judgement uncertainty and uncertainty related to the pair-wise comparison process as described in Chapter 6 (Eq. 6-1 – Eq. 6-16).

In order to calculate exposure, sensitivity and resilience using Eq. 5-6, Eq. 5-7 and Eq. 5-20, the relative weights of exposure (i.e., $W_{E_{Com}}$), sensitivity (i.e., W_S) and resilience (i.e., W_{RE}) were calculated. As four groups of locally experienced social workers (each includes four members, therefore sixteen members in total) participated in the pair-wise comparison process, the $W_{E_{Com}}$, W_S and W_{RE} are the weighted relative considering the participants' experience.

Consequently, their expert index (i.e., EI) (see Chapter 6) was initially calculated and presented as Table 7-4. Briefly, based on the definition of expert experience (i.e., EE) whose range is from 1 (not very significant) to 9 (very significant) (see Section 6.3 in Chapter 6), then the competence of each social worker in a village, EI_{sw}, is obtained using Eq. 6-9. For example, the experience of the four social workers are 23, 18, 15 and 10 years respectively for Ganyan village, and therefore each EE is allocated to 9, 7, 6 and 4, thereby, EI_{sw}^1, EI_{sw}^2, EI_{sw}^3 and EI_{sw}^4 are equal to 0.35, 0.27, 0.23 and 0.15 respectively.

Based on Table 7-4, the weighted relative weights of exposure, sensitivity and resilience for four villages were calculated using the fuzzy AHP technique (see Chapter 6) presented in Table 7-5.

Table 7-4: Expert index

	Ganyan village	**Xiniu village**	**Xiawu village**	**Shuiying village**
Social worker 1 (EI_{sw}^1)	0.35	0.33	0.35	0.32
Social worker 2 (EI_{sw}^2)	0.27	0.26	0.27	0.3
Social worker 3 (EI_{sw}^3)	0.23	0.22	0.24	0.24
Social worker 4 (EI_{sw}^4)	0.15	0.19	0.14	0.14

Table 7-5: Weighted relative weights of exposure, sensitivity and resilience

	Ganyan village	Xiniu village	Xiawu village	Shuiying village
Exposure	0.537	0.375	0.44	0.506
Sensitivity	0.242	0.476	0.485	0.419
Resilience	0.221	0.149	0.075	0.075

7.5.1 Exposure results

Exposure analysis results are the relative exposure scores obtained by two stages. Firstly, the relative importance (or weights) of risk events and categories identified in section 7.4 were calculated using the FAHP technique in Section 7.5.1.1. Secondly, the weighted relative exposure scores were calculated considering the values of risk events, categories, their relative weights and weighted relative importance of exposure in Section 7.5.1.2.

7.5.1.1 Pair-wise comparison scores

As three road managers participated in the pair-wise comparison process each set of weights each road manager generates takes into account the manager's competence. The expert index for three road managers were calculated as EI_{rm}^{1}, EI_{rm}^{2} and EI_{rm}^{3} that are equal to 0.39, 0.35 and 0.26 respectively in the light of the approach for expert index for social workers described above. Accordingly, the results of the weighted relative weights of risk events and categories are given in the Table 7-6.

These indicate that risk events related to health have the highest importance relative to the other five categories. Within this category, the risk event for disruption of emergency services is viewed as being most important compared with others, while loss of chance to buy medication is conversely considered to be the least important.

The second most important risk category was found to be employment. Although the risk category associated with agriculture is ranked third, the values of relative weights for employment and agriculture are approximately equal. For employment, the risk event related to employment attendance was given the highest weight, while loss of access to perform traditional marriage/ funeral activities the was given the lowest weight. For agriculture, the risk events related to transportation of (1.) tobacco, (2.) water/fertilizer and (3.) grass were considered to have approximately equal weights.

The fourth most important risk category was found to be marketing within which the disruption of access to trading centres was considered to be the most important. It was given a higher weight than the loss of potential trading opportunities which had the lowest weight.

The least two risk categories in terms of their importance were income and consumption, and education. For income and consumption, the most important risk event was associated with the living standard, while the least important risk event was a loss of the chance to have photo services. For education, the risk event related to the disruption of a health educator visiting was given the highest weight score, while the loss of access to school was allocated the lowest.

In addition, a relevant pair-wise comparison process was carried out by four groups of social workers for the relative importance of exposure, sensitivity and resilience. Initially, the expert index for four groups of social workers were calculated and presented in Table 7-5. Based on this, the weighted relative weights of exposure for four villages are presented in Table 7-6.

Table 7-6: Weighted relative weights for risk events and categories

Risk category	**Risk event**	**Weighted relative weights for Risk categories**	**Weighted relative weights for risk events**
Agriculture	The transportation of tobacco leaf	0.1669	0.29723
	The transportation of water/fertilizer for irrigation/fertilization		0.33703

	The transportation of grass for feeding animals (e.g. pigs)		0.31191
	The extension worker's visit		0.05382
Education	Labour training	0.0421	0.21583
	The access to schools		0.05638
	The health educator's visiting		0.72779
Employment	Employee attendance	0.1977	0.57154
	The access to perform the traditional marriage		0.07154
	The access to perform the traditional funeral		0.0747
	The potential opportunities to be employed		0.28223
Health	Buying medication	0.4376	0.02746
	Emergency service		0.55332
	The access to health centres		0.12577
	The access to maternity centres		0.23591
	The immunisation programs		0.05754
Income and consumption	Buying poultry (e.g. chicken)	0.0475	0.05995
	Acquisition of photo service		0.02634
	Buying coals		0.08624
	Buying foods and other things used in home		0.13082
	Transport of material for house construction (e.g. brick, sand, rock)		0.14636
	The selling and buying capacities		0.22606
	The standard of living		0.32435
Marketing	The access to trading centres	0.1082	0.82917
	Potential trading opportunities		0.17083

7.5.1.2 Risk events, categories and overall risk scores

Through deriving the relevant data (e.g. probabilities of risk event) from road managers, the scores of risk events, categories and overall risk results were obtained and presented in Table 7-7. A risk event score was the weighted relative value determined by the following four steps. Firstly, three values (i.e., three UFNs, see Chapter 6) for probability and consequence of a risk event provided by three road managers were weighted by their competence (i.e., EI_{rm}^1, EI_{rm}^2 and EI_{rm}^3) using Eq. 6-15, and then were summed as weighted probability and consequence values using Eq. 6-10. Secondly, the weighted risk event value was obtained using Eq. 5-2 together with the results from previous step. Thirdly, the weighted value of the risk event was defuzzfied to a single number using Eq. 6-16. Fourthly, the weighted relative value was determined by the weighted risk event value for a village divided by maximum weighted value of that risk for the four villages considered using Eq. 5-4.

Accordingly, the risk category scores were obtained by summing the weighted relative values of corresponding risk events multiplied by weighted relative weights of those risk events stated in Table 7-6 via Eq. 5-5. As a result, the overall risk scores, in terms of relative values, were acquired using three stages using Eq. 5-6. Firstly, each risk category score multiplied by the weights of the six risk categories in Table 7-6 was summed. Secondly, such summation was multiplied by the weighted relative weight of exposure in Table 7-2 (i.e., weighted overall risk scores). Thirdly, the overall risk scores (or weighted relative overall risk/exposure scores) were obtained via the weighted overall risk scores divided by the maximum weighted overall risk score for all four villages.

From Table 7-7, it may be seen that Xiniu village has the highest overall risk score of 1 relative to other three villages. This is because 22 risk events out of 25 have the highest risk scores compared with other three villages so that Xiniu village has the highest scores for all six risk categories. The second highest risk score was obtained for Ganyan village (0.983) due to its relatively high scores for agriculture, education, health and marketing. Overall risk scores of 0.655 and 0.681 were computed for Xiawu and Shuiying villages respectively.

Table 7-7: Scores for risk events, categories and overall risk

Risk category	Risk event	Ganyan village		Xiniu village		Xiawu village		Shuiying village	
		Risk category score	Risk event score	Risk category score	Risk event score	Risk category score	Risk event scores	Risk category score	Risk event score
Agriculture	The transportation of tobacco leaf	0.44	0.989	0.667	1	0.3374	0.425	0.3764	0.211
	The transportation of water/fertilizer for irrigation/fertilization		0.517		1		0.607		0.775
	The transportation of grass for feeding animals (e.g. pigs)		0.484		1		0.412		0.639
	The extension worker's visit		0.647		1		0.817		0.631
Education	Labour training	0.0696	0.586	0.126	1	0.0627	0.401	0.0546	0.512
	The access to schools		0.466		1		0.365		0.375
	The health educator's visiting		0.602		1		0.723		0.411
Employment	Employee attendance	0.5003	0.398	0.732	1	0.5096	0.335	0.4562	0.679
	The access to perform the traditional marriage		0.604		0.7		1		0.6
	The access to perform the traditional funeral		0.844		1		0.772		0.509
	The potential opportunities to be employed		0.685		1		0.47		0.519
Health	Buying medication	1.5616	0.371	2.149	1	1.1244	0.276	0.9638	0.366
	Emergency service		0.936		1		0.548		0.349
	The access to health centres		1		0.911		0.678		0.737
	The access to maternity centres		0.637		1		0.411		0.397

	The immunisation programs		0.625		1		0.656		0.354
Income and consumption	Buying poultry (e.g. chicken)	0.1698	0.351	0.305	1	0.1977	0.358	0.1646	0.326
	Acquisition of photo service		0.669		1		0.563		0.46
	Buying coals		0.75		1		0.649		0.88
	Buying foods and other things used in home		0.511		1		0.419		0.455
	Transport of material for house construction (e.g. brick, sand, rock)		0.875		0.416		1		0.568
	The selling and buying capacities		0.204		1		0.589		0.344
	The standard of living		0.211		1		0.583		0.431
Marketing	The access to trading centres	0.14112	0.589	0.216	1	0.1136	0.399	0.1024	0.358
	Potential trading opportunities		0.715		1		0.651		0.588
Overall risk scores		0.983		1		0.655		0.681	

7.5.2 Sensitivity results

The sensitivity scores were obtained by two stages. Firstly, the relative importance (or weights) of the sensitivity determinants identified in Chapter 5 were calculated using the FAHP technique in Section 7.5.2.1. Secondly, the relative weighted sensitivity scores were calculated considering the values of sensitivity determinants and relative weights for sensitivity determinants and sensitivity itself (see Table 7-2) in Section 7.5.2.2.

7.5.2.1 Pair-wise comparison scores

For each village four social workers participated in the pair-wise comparison process. Their EIs are presented in Table 7-1. Based on this, the results of the weighted relative weights (or importance) of sensitivity determinants and cargo- and passenger-related transport services are presented in the Tables 7-8 and 7-9. From Table 7-8, it may be seen that all four villages consider investments (*In*) as being the most important compared with stores (*St*) and claims (*Cl*). The stores and claims are ranked second and third most important for Ganyan and Xiniu villages, while Xiawu and Shuiying villages have the opposite ranking for claims and stores.

Productive assets (*Pa*) were the most significant for Ganyan, Xiawu and Shuiying villages, but the least significant for Xiniu village. Furthermore, the productive assets of land for livestock (*Li*) and crop (*Cr*) were ranked the most and the least important in Xiniu and Xiawu villages respectively. Conversely, Ganyan and Shuiying villages considered *Li* and *Cr* as the least and the most important.

Human productive assets (*Ha*) were considered as the second important for Xiniu, Xiawu and Shuiying villages and the third importance for Ganyan village. In human assets, four villages have consensus with respect to the number of total population (*Tp*) and disabled (*Dis*) as being first and second most significant determinants. The number of elderly (*El*) was ranked the third most significant for Ganyan, Xiawu and Shuiying villages and the fourth for Xiniu village.

With respect to the collective assets (*Ca*), only Xiniu village was found to be the most important among the four villages. Ganyan village considered *Ca* as the second most important, while Xiawu and Shuiying villages ranked it as the least importance. Furthermore, the rural road route value (*Rv*) in collective assets was considered to be the most significance compared with access to an all-season road (*RAI*) and rural transport services (*Ts*) for all four villages.

Table 7-8: Weights for the sensitivity determinants

Sen det.	Sub sen. det.	Sub-sub sen. det.	**Ganyan village**			**Xiniu village**			**Xiawu village**			**Shuiying village**		
			Sen. det. we.	Sub sen. det. we.	Sub-sub sen. det. we.	Sen. det. we.	Sub sen. det. we.	Sub-sub sen. det. we.	Sen. det. we.	Sub sen. det. we.	Sub-sub sen. det. we.	Sen. det. we.	Sub sen. det. we.	Sub-sub sen. det. we.
In	*Ha*	*Tp*	0.768	0.246	0.445	0.715	0.287	0.473	0.757	0.281	0.398	0.704	0.291	0.4
		Ch			0.074			0.107			0.147			0.111
		El			0.122			0.152			0.095			0.125
		Dis			0.233			0.193			0.273			0.3
		Wo			0.081			0.034			0.042			0.031
		Fh			0.046			0.041			0.045			0.033
	Pa	*Li*		0.41	0.219		0.283	0.516		0.448	0.577		0.488	0.391
		Cr			0.781			0.483			0.423			0.609
	Ca	*Rv*		0.344	0.69		0.43	0.743		0.271	0.563		0.221	0.713
		RAI			0.09			0.167			0.169			0.138
		Ts			0.22			0.09			0.268			0.149
St			0.169			0.196			0.101			0.123		
Cl			0.063			0.09			0.142			0.173		

For table 7-9, it may be seen that four villages consider cargo-related transport service (Ts_c) as being the most and far more important than passenger-related transport service (Ts_p). Moreover, all villages are in agreement regarding the allocation of weights for five cargo-related rural transport services and five passenger-related rural transport services.

Table 7-9: Weighted relative weights for cargo- and passenger-related transport services

Ts		**Ganyan village**		**Xiniu village**		**Xiawu village**		**Shuiying village**	
		Weights for Ts_c, Ts_p	Weights for specific transport services in Ts_c, Ts_p	Weights for Ts_c, Ts_p	Weights for specific transport services in Ts_c, Ts_p	Weights for Ts_c, Ts_p	Weights for specific transport services in Ts_c, Ts_p	Weights for Ts_c, Ts_p	Weights for specific transport services in Ts_c, Ts_p
Ts_c	Wheelbarrow	0.853	0.026	0.87	0.026	0.844	0.028	0.842	0.032

	Animal drawn cart		0.05		0.053		0.055		0.062
	Tractor		0.112		0.108		0.119		0.126
	Mini lorry		0.269		0.255		0.259		0.27
	Lorry		0.543		0.558		0.539		0.51
	Bicycle		0.028		0.031		0.028		0.025
	Motorcycle		0.052		0.053		0.058		0.054
Ts_p	Motorised tricycle		0.11		0.152		0.121		0.111
	Private car	0.147	0.528	0.13	0.502	0.156	0.494	0.158	0.464
	Bus		0.282		0.262		0.299		0.346

7.5.2.2 Sensitivity determinant scores and overall sensitivity scores

Through deriving the relevant data (e.g. road user for the route from the village to district centre) from road managers, social workers and academics, the scores of sub-sub-, sub-sensitivity determinants, sensitivity determinants, and overall sensitivity results were obtained and presented in Table 7-10.

Similar to the exposure calculation above, the sub-sub sensitivity determinants, i.e., livestock (*Li*), crop (*Cr*), rural road route values (*Rv*), rural access index (*RAI*) and rural transport services (*Ts*), were firstly calculated using Eq. 5-10 – Eq. 5-11, Eq. 5-15 – Eq. 5-17 in conjunction with involved (a.) relative weights in Tables 7-8 and 7-9, (b.) fuzzy calculation related to Eq. 6-10 – Eq. 6-16, and (c.) expert index for social workers (EI_{sw}) in Table 7-4, rural road managers (EI_{rm}, see Section 7.5.1) and road subject related academics (EI_{ac}, i.e., $EI_{ac}^1 = 0.89$, $EI_{ac}^2 = 0.18$). Therefore, the value for *Li, Ar, Rv, RAI and Ts* is weighted relative value. Based on this, productive assets (*Pa*) and collective assets (*Ca*) were calculated using Eq. 5-10 and Eq. 5-13.

Following the calculation of human assets (*Ha*) using Eq. 5-9 in conjunction with (a.) relative weights of determinants of *Ha* in Tables 7-8, (b.) fuzzy calculation related to Eq. 6-10 – Eq.

6-16, and (c.) expert index for social workers (EI_{sw}) in Table 7-4, the investment was calculated using Eq. 5- 8 in the light of the calculated *Ha, Pa and Ca* and their relative weights in Table 7-8. Using Eq. 5-18 and Eq. 5-19, the stores (*St*) and claims (*Cl*) were calculated.

Consequently, the weighted relative sensitivity score was calculated using Eq. 5-7 through (a.) the computed *In*, *St* and *Cl*, (b.) their relative weights in Table 7-8 and (c.) relative weight of sensitivity itself in Table 7-5.

From the table 7-10, it may be seen that the Shuiying village has the relatively lowest score of 0 for human assets, thereby, it may make the relatively lowest contribution to its sensitivity. The Xiawu village has the second lowest score of 0.0563 for human assets, the Xiniu village has the third lowest score of 0.0934 and the Ganyan village has the highest score of 0.1264. As a result, their contribution to their own sensitivities gradually increases. For productive assets, Shuiying village has the relatively highest score of 0.9999912, even if the values for its livestock and crop indicators were ranked into second compared with other three villages.

For collective assets, Xiniu village has the relatively highest score of 1 for rural road route value, implying the worst road route value compared with remainder villages. Additionally, all villages have scores of 0 for all season access, this reveals that no population in each village live in being away (i.e., 2 km radius) from the all-season road with good or fair pavement condition (see Section 1.1 in Chapter 1). In terms of rural transport services, Ganyan has the relatively highest score of 0 implying the relatively best transport services amongst all villages considered. Overall, Shuiying has the relatively highest score of 0.9586 for collective assets, implying the worst condition of collective assets so as to increase its sensitivity at most. Xiawu village has the second highest score of 0.8551, thereby, it has the second worst collective assets condition. Ganyan village has the best collective assets condition.

In terms of stores and claims, Xiawu village has the relatively highest score of 1 revealing the worst stores and claims compared with others, so as to increase its sensitivity at most. Consequently, Xiawu village has the relatively highest sensitivity score of 1 meaning the most sensitive to exposure. The Ganyan village has the lowest sensitivity score of 0.3718, that is the least sensitive to exposure.

Table 7-10: Scores for sensitivity determinants and overall sensitivity

Sub -sub sen. det.	Sub sen. det.	Sen. det.	Sensitivity	**Ganyan village**				**Xiniu village**			
				Sub-sub sen. det. sc.	Sub sen. det. Sc.	Sen. det. sc.	Overall sensitivity score	Sub-sub sen. det. sc.	Sub sen. det. Sc.	Sen. det. sc.	Overall sensitivity score
	Ha				0.1264				0.0934		
Li	*Pa*			0.99997964	0.9999898			1	0.9989955		
Cr				0.99999262				0.99999075			
Rv	*Ca*	*In*	*S*	0.3941	0.2719	0.5346	0.3718	0.6883	0.5692	0.5545	0.9489
RAI				0				0			
Ts				0				*0.642*			
		St				0.609				0.989	
		Cl				0.089				0.977	
Sub-sub sen. det.	Sub sen. det.	Sen. det.	Sensitivity	**Xiawu village**				**Shuiying village**			
				Sub-sub sen. det. sc.	Sub sen. det. Sc.	Sen. det. sc.	Overall sensitivity score	Sub-sub sen. det. sc.	Sub sen. det. sc.	Sen. det. sc.	Overall sensitivity score
	Ha				0.0563				0		
Li	*Pa*			0.99993672	0.9999634			0.99998353	0.9999912		
Cr				1				0.99999606			
Rv		*In*		0.5401			1	1		0.6676	0.911

RAI	*Ca*		*S*	0	0.5236	0.6054		0	0.8128		
Ts				0.819				0.67			
		St				1				0.793	
		Cl				1				0.994	

7.5.3 Resilience results

Resilience scores were obtained by two stages. Firstly, the relative importance (or weights) of the resilience determinants identified in Chapter 5 were calculated using the FAHP technique in Section 7.5.3.1. Secondly, the relative weighted resilience scores were calculated considering the values of the resilience determinants (i.e. community participation) and weighted relative weight of resilience itself presented in Table 7-2 as given in Section 7.5.3.2.

7.5.3.1 Pair-wise comparison scores

The three local rural road managers, as stated in Section 7.5.1, also participated in the pair-wise comparison process for resilience, hence, EI_{rm}^{1}, EI_{rm}^{2} and EI_{rm}^{3} were 0.39, 0.35, 0.26 respectively and were used to calculate the weights of the determinants of resilience presented in Table 7-11.

From Table 7-11, the supervisors were regarded as the most significant resilience determinant relative to labourers, technicians and monitoring. The technicians were considered to be the second significant. Following technicians, although labourers were more significant than monitoring, both values are approximately equal.

Table 7-11: Weighted relative weights of resilience determinants

Labourer	Supervisor	Technician	Monitoring
0.079	0.484	0.371	0.066

7.5.3.2 Overall resilience scores

Similar to the exposure calculation in Section 7.5.1, the overall resilience scores were calculated using Eq. 5-20 in conjunction with Table 7-11 and Table 7-5. The resulting scores are presented in Table 7-12. From the table, it may be seen that Ganyan village has the relatively highest resilience score of 1 implying the relatively strongest capacity to alleviate vulnerability. Xiniu village has the second highest resilience score of 0.629, while Shuiying village has the third highest resilience score of 0.411. Xiawu village has the last resilience score of 0.295 implying the relatively weakest resilience capacity to decrease vulnerability.

Table 7-12: Scores for overall community resilience

	Ganyan village	**Xiniu village**	**Xiawu village**	**Shuiying village**
Resilience score	1	0.629	0.295	0.411

7.6 Vulnerability evaluation

7.6.1 Vulnerability results

The vulnerability results obtained are presented in Table 7-13. MATLAB© software (The Math Works, Inc., 2020) was employed to implement the fuzzy rule-based system described in Chapter 6 and to calculate quantitative vulnerability results for the four villages (The

MATLAB© code for the developed fuzzy system can be found in Appendix G). Furthermore, using Eq. 6-26 to Eq. 6-30 in conjunction with the four quantitative results of vulnerability, the vulnerability category was calculated and is presented in Table 7-13.

Table 7-13: Qualitative and quantitative scores of overall vulnerabilities for the four villages

	Overall vulnerability scores	Vulnerability category
Xiawu village	0.989	Very high: 100%
Xiniu village	0.909	High: 100%
Shuiying village	0.732	Moderate: 100%
Ganyan village	0.6	Low:62.5% Moderate: 37.5%

In the light of the quantitative and qualitative results of vulnerability for the four villages, the most vulnerable village is Xiawu village, thereby, the research recommends the highest priority for road investment. The second and third vulnerable villages are Xiniu and Shuiying villages respectively, therefore, they should have the second and third priority for road investment. The least vulnerable village is Ganyan village, hence, this research recommends the lowest priority for road investment.

7.7 Verification of the results

The results of the case study were verified using expert participation. One-to-one interviews with four employees of four villages who are very familiar with the four villages' situation in terms of exposure, sensitivity, resilience and vulnerability were undertaken. During the interviews, the resultant rankings of exposure, sensitivity, resilience and vulnerability for the four villages in the form of a questionnaire (see Appendix F) were given to the members of staff. Overall, the members of staff confirmed that the results are sensible and justified.

7.8 Summary

This chapter demonstrated the vulnerability assessment model in the fuzzy environment using a case study. Firstly, the study area was depicted. Secondly, the data providers and data collection process (consisting of familiarisation of data provider, training for data provider and collection of data provider's opinion) were described. Based on the process, thirdly, the vulnerability identification was carried out, i.e., the risk events identified in Chapter 5 were confirmed and the newly risk events were identified for four villages. Fourthly, the weighted relative overall scores for exposure, sensitivity and resilience for the four villages were calculated by aggregating the scores of determinants of exposure, sensitivity and resilience and their relative weights. Based on the calculated scores of exposure, sensitivity and resilience, sixthly, the results of vulnerability for the four villages were computed in qualitative and quantitative terms.

The next chapter will summarise the research and discuss the limitations of the research.

CHAPTER 8 DISCUSSION

This thesis has described the development of a methodology through which a vulnerability assessment model with capacity to deal with fuzzy concept related uncertainty was developed. Using this model, the rural road access vulnerabilities of communities can be assessed, and the output of the assessment could be used a basis for prioritising road investments.

8.1 Summary of the research and progress made towards meeting the research objectives

The research undertaken and the progress made towards meeting the objectives given in Section 1.3 is as follows:

1. Identification of research gap between road investment prioritisation and vulnerability assessment

In order to identify an appropriate approach for addressing the impact of undesirable road condition/road access loss on rural community vulnerability, a review of relevant literature was conducted (see Chapters 2 and 3). In Chapter 2, the literature found CBA and MCA approaches have been used for road investment appraisal and could be useful for the task at hand, although no examples were found of their use to take into account the impact of hazards on access and the ability of communities to cope and adapt to such hazards. The literature review in Chapter 3 identified that vulnerability-based approaches could be used to consider the likelihood and impact of reduced access through which the road investments can be prioritised. The majority of approaches reviewed identified adopted R-H models which consider only environment-related vulnerability determinants. However, a few studies were identified that consider vulnerability determinants more comprehensively. Such EV models were therefor chosen for the task at hand since they enable vulnerability to be considered in terms of exposure to environmental hazards, the sensitivity of the communities to such hazards and the resilience or adaptive capacity of the communities.

Consequently, objectives 1 and 2 in Chapter 1 were achieved, i.e., CBA and MCA were identified as road investment prioritisation approaches, whilst EV models were identified to be the most appropriate approach for vulnerability assessment due to their more comprehensive inclusion of vulnerability determinants.

2. **Development of a methodology to assess rural communities' road access vulnerabilities through which the road investments can be prioritised**

Based on the findings from the literature review (Chapters 2 and 3), an approach described in Chapter 4 was developed to guide the development of a vulnerability assessment model which can deal with fuzzy related uncertainty in a methodological manner (the vulnerability assessment model was described in 3-4 points below). The approach consisted of a research methodology, a theoretical framework, addressing uncertainty, and a case study to demonstrate the viability of the theoretical framework. The research methodology described the sequential steps used to undertake this research. The resulting theoretical framework developed an EV model using an AHP-based assessment framework which utilised the an AHP based MCA approach. In order to enhance the robustness of the developed model so that it can take into account uncertainty, a uniform format number (UFN), fuzzy AHP and fuzzy system was incorporated within the framework (see Point 4 below). Individual interviews utilising structured questionnaires were used successfully for data collection.

3. **Vulnerability identification and analysis**

Based on the theoretical framework developed, in particular the methods described in Section 4.2 in Chapter 4, potential determinants of EV vulnerability model were identified and analysed. This process is described in Chapter 5.

Vulnerability was decomposed into exposure, sensitivity and resilience. First, exposure was defined as disruptive access due to undesirable road conditions or/and loss of road access. These situations negatively impact agriculture, education, employment, health, income consumption, and marketing. Furthermore, each (or hazardous group) consisted of corresponding individual hazardous events which were quantified using Eq. 5-1 to Eq. 5-4 (see Figure 5-2 (a-c)). Eq. 5-3 and Eq. 5-4 utilised normalisation operator (i.e., the value of a hazardous event for a community divided by the maximum value of the hazardous event for the community). This enabled the addition of hazardous events related to undesirable road condition and ones related to road access provision loss as shown in Eq. 5-5, as the unit (e.g. the number of people affected) of former is different from the unit (e.g. the increase in travel time) of latter. Therefore, hazardous groups were calculated using Eq. 5-5 via Eq. 5-1 to Eq. 5-4. Based on those five equations, Eq. 5-6 was developed to calculate the relative exposure scores for the communities considered.

Sensitivity was defined as a component of vulnerability that describes the community's ability to protect itself against the impacts of exposure. For the purposes of the research, and following approaches identified in the literature for other applications, a community's sensitivity was defined in terms of its assets (see Figures 5-1 and 5-3). It was assumed that the greater the asset store of a community the less vulnerable it would be to lack of access. A community's assets were disaggregated into investments, stores and claims. The investments were assets that could provide an income, and included human assets, productive assets and collective assets. Briefly, human assets were identified to encompass total population, children, elderly, disabled, women and female-headed household. The greater the total population, the higher income level the community would be, then the less sensitive to the exposure. Conversely, the greater the number of children, elderly, disabled, women and female-headed household, the less community's income and the more sensitive the community. Productive assets referred to pasture and arable land for livestock and crop. The greater the amount of pasture and arable land the higher the income level for the community, and thereby, the less sensitive the community would be to loss of access. Collective assets focused on rural road assets and rural transport services. Rural road assets were regarded as (a.) road routes from the community to amenities, and (b.) all-season access. Rural transport services included passengers- (e.g. bus) and cargo-related (e.g. lorry) transport services. Therefore, the more road routes, all-season access and rural transport services for a community, the less sensitive the community would be. Stores represented the storage of surplus following immediate consumption. Claims were intangible assets, i.e., a kind of ability to ask for help from outside. These identified sensitivity determinants were represented using Eq. 5-8 to Eq. 5-19. Of which, Eq. 5-9, Eq. 5-11 – Eq. 5-12, Eq. 5-15 – Eq. 5-19 employ the normalisation operator for reason of heterogeneous units. Based on those 12 equations, Eq. 5-7 was developed to calculate the relative sensitivity scores for the communities considered.

Third, resilience referred to a community's ability to adapt to lessen future impacts of lack of rural access provision, thus, it represented a medium- or/and long-term response following exposure. This is different from the sensitivity above that is related to asset-based coping capacity, i.e., an immediate reaction to exposure. In the study, community participation was utilised for representing resilience, i.e., the degree for a community to participate in road works (e.g. maintenance, rehabilitation). The higher degree of community participation in road works, the more number of community members participate in the road works, the faster the road damaged by geo-hazards could be repaired, the less impacts from road risks (see Figure 5-2 (a-c)) the community could withstand, the more resilient the community would be. Resilience in terms of community participation was determined by Eq.20 which provides the relative resilience scores for the communities considered.

Eq. 5-5, Eq. 5-7 and Eq. 5-20 were designed to limit the numerical range of relative scores of exposure, sensitivity and resilience to between 0 and 1.

4. Dealing with uncertainty

Uncertainties within road asset management (see Chapter 2) and within vulnerability assessment (Chapter 3) were identified, i.e., parameter uncertainty/judgement uncertainty, uncertainty related to related to pair-wise comparison process and aggregation uncertainty. In Chapter 2, fuzzy related approaches (i.e., membership function and fuzzy AHP) were identified as suitable for dealing with parameter uncertainty and uncertainty related to the pair-wise comparison process. Such approaches were found to be more suitable than widely used probabilistic approaches (e.g. Monte Carlo simulation), as they were considered to be more straightforward for an expert (as a data provider, see Chapter 4) to express the value of a parameter using natural language. In Chapter 3, fuzzy logic was preferred to address aggregation uncertainty compared with classical and probabilistic logic. This is because classical logic fails to take into account uncertainty (such as a proposition without an absolute truth value). Besides, probabilistic logic based on certainty factors and Bayesian theorem methods assumes the independence of elements considered. In the research, vulnerability and its components (i.e., exposure, sensitivity and resilience) are not independent. In addition, probabilistic logic is unable to deal with fuzzy/vague information in a proposition, so that a given probability for the fuzzy/vague information causes ambiguity. For example, given that the probability for "it will be raining tomorrow" is 0.7, raining is a vague piece of information, as this leaves a doubt of is the amount of rainfall. However, fuzzy logic, as an approach to computing with words, is competent to characterise/quantify fuzzy/vague information using fuzzy set/membership function (Zadeh, 1996). Therefore, fuzzy logic solves the doubt by quantifying the word 'raining'.

Consequently, Objective 3 in Section 1.3 in Chapter 1 was achieved, i.e., fuzzy concept related approaches were identified for addressing uncertainty in data analysis. Based on this, the UFN, Buckley's fuzzy AHP and Mamdani-based fuzzy system were identified and described in Chapter 4 to deal with the aforementioned uncertainties. UFN was used to deal with uncertainty associated with estimates provided by experts (see Table 6-1 in Chapter 6). UFN was found to be useful for this purpose since it enables experts to use natural language when providing estimates of parameters. This was found to be helpful in enhancing confidence of the judgement of experts during data collection and was felt therefore to improve the reliability of the data collected. UFN is the result of transforming natural language into trapezoidal fuzzy number. Based on this, the fuzzy number operations (see Eq. 6-11 – Eq. 6-14) were given for fuzzy calculation on Eq. 5-1, Eq. 5-2, as experts directly provide natural language-based data for parameters in those equations. When several experts participate in such data collection, Eq. 6-15 was developed to consider expert competence for weighted relative score calculation.

In order to solve uncertainty related to pair-wise comparison process, trapezoidal fuzzy numbers were employed to replace exact numbers for the representation of linguistic descriptors (see Table 6-2). Using geometric mean method suggested by Buckley (1985), AHP was modified as Buckley's fuzzy AHP for relative weight calculation (see Table 4-3 for justification of Buckley's fuzzy AHP). When several experts participate in pair-wise comparison process, Eq. 6-8 was developed to consider expert competence (see Expert index in point 5 below) for weighted relative weight calculation.

For aggregation uncertainty, the Mamdani-based fuzzy system was used to model the mathematical relationships between exposure, sensitivity and resilience in the vulnerability model. To achieve this, fuzzy rules were used to represent the possible mathematical relationships between vulnerability and its three components (see Table 6-3). Once the fuzzy rules were established, the relevant membership functions (see Eq. 6-31 to Eq. 6-35) were developed to numerically express vague information (i.e., very low, low, moderate, high and very high) on fuzzy rules. This enabled the results of exposure, sensitivity and resilience obtained in Chapter 5 to be fuzzified as qualitative terms (e.g. low, moderate or high) through which the corresponding fuzzy rule(s) was/were activated. Using Mamdani's min and max operators and defuzzification (i.e., centre of area, see Eq. 6-40), the vulnerability values were inferred into qualitative and quantitative formats.

5. The use of vulnerability assessment model (case study)

A case study was undertaken to demonstrate the vulnerability assessment model developed. The case study consisted of comparing the vulnerabilities of Ganyan, Xiniu, Xiawu and Shuiying villages in Changchunpu District in Guizhou province in China. Although some locally available data (e.g. the type of rural transport service) was obtained and the relevant literature was reviewed, expert opinion described in Chapter 4 was recognised to be needed to obtain most of the data required for the model. Consequently, 21 experts who have specialist skills and knowledge in road engineering, geo-hazard identification, the rural society and the local economy, participated in the research. Of which, three rural road managers with a strong road engineering background obtained by working for the road department in Changchunpu district government participated. They are very familiar with and, have in (a.) significant experience in dealing with the impacts of geo-hazards on the specific road sections historically, (b.) knowledge of the potential geo-hazards which might impact the assessed rural roads, and (c.) the capacity/power to mobilise relevant resources for the repair of rural road assets in this district. The experts were consulted by means of structured interviews to confirm the hazardous events causing road access loss and the associated undesirable road conditions. Thereafter, they estimated the numerical value of geohazard frequency, the impact of potential hazardous events and their relative importance (weights). In addition, (1.) the numerical value for (a.) users of road route from the local community to district centre, (b.) labourers, supervisors, technicians and monitors, and (2.) the relative importance of elements in (b.) (see Chapter 7).

Sixteen local social workers (four for each village) with considerable experience, knowledge and familiarisation with respect to rural society and the local economy were also identified. The social workers were consulted with respect to the numerical estimation of parameters related to the sensitivity determinants (e.g. the number of women, rural transport services). Additionally, they were asked to provide the relative weights of the sensitivity determinants considered. In addition to this, two road-subject-related academics were asked to estimate the IRI of the roads leading villages to district centre.

The competences of the 21 invited experts were gauged by means of expert indices. The indices were calculated by initially transforming their number of years of experience into an expert experience scheme ranging from 1 to 9 (1 represents not significant, 9 very significant) (see Chapters 6 and 7 for expert index and expert experience). For example, for a group of experts who were consulted with the same questions, the expert with the greatest experience was allocated a value of 9. The allocation of expert experience scheme for expert with second highest experience year was the calculation that 9 is multiplied by the result of the number of second highest experience year divided by the number of the greatest experience year. Such allocation for experts with (third, fourth etc.) highest experience year was based on such calculation (see Section 7.5). Thereafter, Eq. 6-9 was used to calculate the expert index for each member of the group.

Based on the data provided by the 21 experts and their calculated expert indices, the vulnerability assessment model was used to calculate the relative vulnerabilities qualitatively and quantitatively for the four villages. Through using this model, rural road managers can obtain the road investment implication, i.e., Xiawu village had the highest vulnerability score of the four villages consider and therefore it could be regarded as having the highest priority for road intervention/investment. The village with the lowest vulnerability (i.e., Ganyan village) could similarly be considered to have the lowest priority for road investment. Xiniu and Shuiying had the second and third highest vulnerability scores respectively and therefore, they had second and third priority for road investment.

8.2 Critical review of the Research

1. Vulnerability identification

In the study, vulnerability was defined in terms of the exposure of a rural community to reduced access and the sensitivity and resilience of the community exposed. However, this might be considered to be a narrow understanding of exposure, sensitivity, and resilience.

This is because even if the determinants of exposure, sensitivity and resilience were identified and described fully, such determinants might not be the root cause of vulnerability. The root cause could be institutional (such as cultural and legislative rules) and/or structural (balance and distribution of resources). For example, lack of affordable rural transport service was a reason for causing vulnerability. However, the root cause of vulnerability in terms of transport service could be lack of subsidy-related policy for rural transport operators to ensure adequate and affordable transport service. Under such circumstances, some operators reduce the frequency of their service provision. Or, some may quit this business. Both hinders transport service utilisation of some number of customers. Therefore, this may negatively affect their social and/or economic activities and have knock-on effect on their income, so that their income-related coping capacity may be reduced, thereby, less impact from exposure they can absorb. Consequently, the further research could further explore the root cause of the vulnerability. Additionally, this study assumed that a community was served by one road leading to outside world, as exposure was defined as a community exposed to loss of road access provision and undesirable road condition risks. Further research could further explore potential road risks for a community served by more than one road. It is also noted that the existing exposure model (see Eq. 5-1 – Eq. 5-6) could also be used for considering road risks encountered by the community that has not only one road.

In the study, exposure was disaggregated into hazardous events and hazardous groups. The identification of hazardous events and hazardous groups were based on the benefits of road investment identified by Hine et al. (2015) and Odoki et al. (2008), as little literature with respect to road access loss and undesirable road condition risks was found. For sensitivity, the concept of the asset was employed in order to provide a straightforward and convenient way to measure sensitivity in the vulnerability analysis stage. As shown in Chapter 5, stores and claims were not fully developed. This was because to facilitate data collection and make the model of practical use, it was felt that the determinants required to quantify sensitivity should be readily available and/or easily collected. Nevertheless, further research could facilitate the disaggregation of stores and claims so as to obtain an in depth understanding of them.

The study assumed that women are socially vulnerable (i.e. the presence of women in a community increases the vulnerability score of the community), however some literature conversely characterises women with stronger coping capacities, greater commitment to knowledge of risk and improved social relations (e.g., Steinführer and Kuhlicke, 2007), i.e., women could be considered to contribute positively to reducing sensitivity rather than negatively as assumed in this research. Ajibade et al. (2013) suggest that women's living conditions are dependent upon socio-economic conditions, household structures and geographic locations which vary from place to place; thus, gender alone may not be an accurate measure of social vulnerability. Indeed, Kuhlicke et al. (2011) suggest that gender has little influence on social vulnerability. Despite this, the study considered the number of women in a community as a measure of its social vulnerability based on gender discrimination (e.g. no opportunity for higher paying job), lack of access to resources, rights and means of transport, physical and cultural constraints (see Section 5.2.2.1.1). However, it is recommended that further research explores these aspects further. For example, it might be possible to change in the model, depending on the prevailing social culture and norms, whether the presence of women in a community increase or reduce vulnerability.

In terms of resilience, community participation was used. This was because community participation is a prevailing approach for rural road works in most of developing countries due to higher cost effectiveness than equipment intensive approach. The greater number of community member participants in rural road project, the faster the damaged road could be repaired, then the faster the access recover. Since only one determinant was considered, of all the three determinants of vulnerability, resilience was the least developed. Further research based on work by Birkmann et al. (2013) and others could explore additional means of characterising resilience in terms of adaptation linking to learning and reorganisation (i.e., medium- or/and long-term measure).

2. Vulnerability analysis

Chapter 5 demonstrates the development of indicators for vulnerability determinants identified in the vulnerability identification stage. Although the developed indicators are subjective due to the subjective selection of vulnerability determinants through reviewing the relevant literature, they are all related to the research question (see Section 1.2 in Chapter 1). Despite this, a model which uses indicators might be considered to have several shortcomings. Chang et al. (2015) state that as vulnerability is a complex problem and determined by several interacting social, economic and environmental factors. As such factors could make contribution to differentially temporal and spatial scales of vulnerability (e.g. current vulnerability of a village, future vulnerability of a country), many of factors find it difficult to use perfectly quantifiable variables for their quantification. Additionally, the demand on data would be tremendous when a large number of vulnerability determinants are considered for understanding large number of communities. Nevertheless, despite these shortcomings, Change et al. (2015) also suggest that this approach is ideal for comparative purposes.

An alternative approach for vulnerability analysis described in the literature is the use of deterministic modelling to assess the impacts of geo-hazards on infrastructure (e.g. road, building) and thereby estimate biophysical vulnerability (Lee et al., 2014). However, this approach would also require a large amount of data and it ignores the social dimensions of vulnerability (or social vulnerability) (Koks et al., 2015).

At vulnerability component level, all-season road in sensitivity considered the percentage of population in a community it can serve as a proxy for measure of the physical condition of road assets. This is because rural access is pivotal component for poverty alleviation and socio-economic development (World Bank, 2016). Therefore, the more population the all-season road provides access for, the better the condition of road assets would be.

3. Vulnerability evaluation

Experts normally have excellent and intuitive knowledge with respect to the characteristics and behaviours of a system, even if they do not have the corresponding quantitative model in mind (Sii et al., 2014). In order to facilitate capturing of expert knowledge within such quantitative models, fuzzy rules have been found to be a useful tool by enabling experts to express their knowledge coherently. Consequently, the vulnerability evaluation used a collection of fuzzy rules (such as "IF exposure is very low AND sensitivity is very low AND resilience is very high, THEN vulnerability is very low") (see Chapter 6). However, gathering different domain experts at the same time in same place could be difficult for rule generation in the research. Consequently, an additive approach suggested by Preston et al. (2009) was used for fuzzy rule generation, i.e., vulnerability was determined by adding together exposure, sensitivity and resilience. A scale of 1 to 5 was used to represent five significant levels (from very low to very high) of exposure and sensitivity and one of -1 to

-5 represent five significant levels of resilience (i.e. 1 represents very low and 5 very high). Accordingly, this generated a rule base of 125 rules.

Each of the 125 rules were assumed to have the same importance, which is in contrast to recommendations in the literature. For example, Sii et al. (2014) suggest that it is inappropriate to have fuzzy rules with identical importance, since there might be some conflicting rules. In other words, rules that have the same antecedent but a different consequent, such as (a.) "IF exposure is very high AND sensitivity is very high AND resilience is very low, THEN vulnerability is very high"; (b.) "IF exposure is very high AND sensitivity is very high AND resilience is very low, THEN vulnerability is low". However, the rules developed for this research were not conflicting (see Table 6-3) and therefore the assumption for identical rule importance is proper.

As only 125 rules were considered in the study, the requirement for the computational cost to run the fuzzy model (see Section 6.5) using ©MATLAB software (The Math Works, Inc., 2020)) was limited, which is not significant. Nevertheless, if the number of rule increases, while the number of scale (i.e., significant level (e.g. low, high etc.)) for exposure, sensitivity, resilience and vulnerability increases, then more computational cost is required. To end this, a technique named as singular value decomposition suggested by Ross (2005) could be employed.

4. Expert participation

The developed vulnerability assessment model required a significant amount of information provided by experts. Hazardous events for the communities considered were identified using available data (from the literature review, see Figure 5-2 (a-c)) and canvassing three rural road managers' opinions by means of structured questionnaires which were utilised to facilitate interviews. Similarly, three rural road managers were consulted to determine the relative weights of the exposure determinants (see Table 7-6), for resilience determinants (see Table 7-11). Three relative weights were commonly used for the four villages. However, each village was given a set of their own relative weights for vulnerability components (see Table 7-5), sensitivity determinants (see Table 7-8), cargo- and passenger-related transport services (see Table 7-9) by a group of social workers working for their own village. Although it did not occur, experts could also have been consulted to (a.) generate rules for triangulation, i.e., expert produced rules can be compared with rules generated by aforementioned additive approach, and only rules confirmed by experts and such approach could be used; (b.) allocate the relative weights of each of the rules confirmed. Both could assist improving the accuracy and reliability of the rules used.

The advantages of using experts include (a.) taking advantage of the experts' knowledge and local experiences for identifying actual hazardous events that might happen in candidate villages, and (b.) avoid any bias that might be happen, i.e., only hazardous events identified by at least two road managers were considered.

Nevertheless, the participation of experts could be improved using more interactive methods of expert elicitation (e.g. Delphi method) and by facilitated workshops rather than by the individual consultation methods used in the research. A facilitated workshop would enable experts to discuss their opinions and to share their expertise so as to reach a higher possibility for identifying complex potential hazardous events by brainstorming. In addition, the workshops could assist avoiding bias and building a consensus amongst experts via group discussion. Such facilitated workshops were not employed herein because of resource and scheduling constraints.

Twenty-one experts participated – this number seems to be similar to those of other similar studies reported in the literature (see Section 4.4 in Chapter 4), albeit not all 21 experts gave their opinions on each parameter. For example, only two road subject related academics provided their judgements on the IRI values for the roads serving the four villages. Ideally, an adequate number of road-engineering-related budgeting specialists could be invited to participate in a workshop where they could discuss and estimate the budget to bring four village roads into their original conditions in the light of the obtained IRI values – and so inform the calculation of road asset value. Based on the estimated budgets, the rural road route value could be calculated using Eq. 5-15. However, due to the limitations of resources and schedule, this study directly utilised the obtained IRI values for rural road route following the valuation approach suggested by Burrow et al. (2013).

From the above, it can be seen that the amount of data collected was limited due to the number of participating experts. Nevertheless, since the purpose of the case study was to demonstrate the vulnerability assessment model developed, it was not considered important for the purposes of illustrating the model to involve in a large and diverse quantity of participants. However, it is also recognised that to provide accurate results there is a need to carefully consider the quantity and diversity of participants for the real application of the model. This would help to improve the accuracy of the results and to avoid bias.

5. The developed vulnerability assessment model

The developed vulnerability assessment model has been designed to inform road investment prioritisation amongst rural communities vulnerable to disruptive access. As such it has focused on aspects associated with the road carriageway. It could be extended to consider other assets such as, drainage assets, bridges, and retaining walls. It should also be noted, that whilst the approach is based on the vulnerability of communities to the loss of road access, the identified investment to reduce vulnerability might not be on the road itself but could for example be associated with drainage assets and retaining walls etc. For example, if a road serving a rural community is vulnerable to being washed away during a severe flood, then an investment to repair the road will not be efficient. Instead, the investment might be better spent on improving road drainage to enhance its the capacity so as to alleviate the impact of flood on the road. This could effectively reduce flood-related road risk. If a road is located in a geo-hazard prone area and is vulnerable to landslides, an investment in a retaining wall where the landslide readily occur could be more effective. This could effectively alleviate landslide road risk.

8.3 Value of the Research

The value of the research has been the development of a vulnerability-based methodology for prioritising road-related investments (e.g. road carriageway, drainage assets, retaining walls etc.) that takes into account the socio-economic considerations of communities and the likelihood of the occurrence of geo-hazards. As such it differs from traditional road investment approaches which are based primarily on consideration of road user costs. Also, where road investment appraisal approaches consider risk, only the likelihood and severity are usually taken into account. Unlike such approaches, the model developed herein takes into account not only the likelihood and impact of stressors, but also considers the resources available to the community to deal with the stressor.

Based on above, the developed approach in the research could assist the user (e.g. budget holder) to gain an in depth understanding of the issues the communities face (i.e., why the community is vulnerable to potential disruptive access), as it encourages the user to carry out a comprehensive analysis of such issues. Based on such understanding, the developed approach further provides a quantitative perspective for the issue, i.e., the scores of rural communities' road access vulnerabilities. As fuzzy logic was used during the development of approach, the qualitative results are also given in the light of the calculated scores of vulnerabilities.

Practically, the application of the developed approach could start with understanding (a.) the factors determining a rural community road access vulnerability, (b.) the meaning of developed indicator related to those factors (e.g. claims indicator reveals that (1.) the percentage of population who cannot receive help in a community; (2.) the potential for a community to acquire assistance is greater than another community), and (c.) suggested approach for data collection. Based on such understanding in conjunction with the review of resource (e.g. availability of time and expert for data collection) at hand, users could select an appropriate approach to optimally obtain the required data with higher reliability and accuracy. This could enable the approach to generate a valid outcome through which road investments for rural communities considered could be prioritised, so that such road investment strategy could be effective and help to appropriately allocated scarce resources under budget constraints. When the resources are suitably assigned to those communities with the greatest needs travel and transport related livelihood activities can be maintained. Therefore, the value of such a road investment strategy (i.e. the value of this research) is to improve local livelihoods and thereby save people's lives.

8.4 Summary

This chapter summarised the major aspects of the research described in this thesis and outlined how the objectives set for the research have been achieved. The research identified the EV-based vulnerability approach as a suitable means to prioritise rural road investment for rural communities where social benefits are difficult to quantify. Fuzzy logic was chosen as an appropriate technique for addressing uncertainty and was incorporated in the EV-based model. In order to test this model, 21 experts participated by means of individual interviews to provide parameters for the model and data associated with exposure, sensitivity and resilience.

In addition, the chapter critically reviewed the proposed vulnerability assessment model. The appropriateness of approaches used to carry out the research was discussed, and recommendations to facilitate further improvements to the model were provided.

Conclusions from the research together with recommendations for future research are presented in the following chapter.

CHAPTER 9 CONCLUSION AND RECOMMENDATION FOR FURTHER RESEARCH

The provision of safe, affordable and reliable rural access is recognised as important for the socio-economic development of rural communities in developing countries. However, most roads serving rural communities in developing countries are unsealed and their passability, particularly in the wet season, is greatly affected by the occurrence of geo-hazards. The occurrence of such hazards is increasing with changes in climate and land use, increasing the vulnerability of local communities. Although the benefits of improved access are well documented, maintenance and rehabilitation budgets in developing countries are severely constrained. As the socio-economic benefits of rural road investment are difficult to quantify, there is a need for a rational and transparent means of prioritising budget to support the most vulnerable communities and to improve the value of money of any investment. To this end, following a review of the literature, it was decided to develop a vulnerability-assessment-based approach which could be used assess the degree to which a rural community is vulnerable to disrupted access.

Based on the methodology described in Chapter 4, a vulnerability assessment model was developed, consisting of vulnerability identification (see Chapter 5), analysis (see Chapter 5) and evaluation (see Chapter 6). The model has the capacity to address uncertainties associated with data and the model form via fuzzy reasoning (see Chapter 6).

The use of the model was demonstrated using four villages in rural China, and the results of the model utilisation were verified as outlined in Chapter 7.

9.1 Accomplished work and main findings

The accomplished work can be summarised as follows:

1. Identifying a research gap in terms of the need for approaches which can be used to prioritise rural road investment considering socio-economic benefits and the risks of hazardous events (see Objective 1 of the research described in Chapter 1);
2. Identifying the appropriate vulnerability assessment approach for rural community road access vulnerability (see Objective 2 in Chapter 1);
3. Identifying suitable fuzzy concept related approaches that can deal appropriate with uncertainties associated with data collected from experts (see Objective 3 in Chapter 1);
4. Developing a vulnerability assessment model with the capacity to address uncertainties (based on the achievement of Objectives 1, 2 and 3 in Chapter 1);
5. Utilizing data collected from four rural communities in China to demonstrate the effectiveness of the developed vulnerability assessment model (see Objective 4 in Chapter 1).

The main conclusions from the work are as follows:

- The majority of existing road investment appraisal approaches (e.g. CBA) have been developed for the strategic road network and those developed for rural roads do not take into account social benefits. Besides, a more holistic vulnerability associated approach which can consider the likelihood of the occurrence of events leading to impaired access was felt to be a more appropriate means of prioritising access roads to local communities. Furthermore, an EV-based vulnerability approach can deal with such prioritisation issue as comprehensively as possible, as it can consider not only the likelihood and consequences (i.e. risks) of undesirable road condition loss of road access (but also the a resources available to a community to respond to the risks.

- In order to use the EV-based vulnerability approach for the task at hand, an MCA – AHP based methodology was found to be appropriate as it allows vulnerability related criteria (a.) to be expressed using monetary and non-monetary terms, (b.) to consider uncertain information, (c.) to be dealt with via expert judgement, and (d.) to be compared with each other in terms of importance. The AHP approach was found to assist with the model development in a relatively straightforward and transparent way.
- For addressing uncertainty involved in the AHP-methodology-based model, fuzzy concept related approaches were identified. Firstly, UFNs was used as it is relatively easy to obtain from experts compared with probability distribution function. Secondly, fuzzy AHP was more appropriate than AHP, as fuzzy AHP can address uncertainty in AHP (i.e., exact number is used to represent linguistic descriptor). Thirdly, fuzzy logic was used to deal with aggregation uncertainty compared with probabilistic logic, as probabilistic logic not only failed to address vague/fuzzy information on rules, but also must consider independently exposure, sensitivity and resilience for vulnerability. However, they are mutual dependent.
- The developed methodology can be successfully used to develop a vulnerability assessment model with the capacity to handle uncertainty in the fuzzy environment.
- Chapter 7 illustrated that the developed vulnerability assessment model could be successfully used in practice.
    - Of those villages considered, Xiawu village was deemed to be the most vulnerable, implying that it should be prioritised first for road investment.

Xiniu, Shuiying and Ganyan villages were found to be the second, third and fourth most vulnerable respectively, thereby, they had the second, third and fourth priorities for road investment.

    - The results of case study using the model were sensible through local staff's verification.

- Canvassing expert opinion was shown to be a viable means for data collection in the absence of required data.
    - Individual interviews and structural questionnaire were found to be the appropriate approaches for eliciting expert opinion.
    - The results presented in Chapter 7 ultimately depend on the range and experience of the experts considered as discussed in Section 4.4.

9.2 Further research

9.2.1 Limitations of the research

Chapter 8 discussed the limitations of the research and identified a number of areas for future research. These are summarised as follows:

- Further exploration of the metrics used to determine stores and claims in the sensitivity determinant of vulnerability and community organisational capacity, financial resource availability associated with resilience. For example, claims could be based on social capital (i.e., ability of actors to securely ensure any benefit as a result of membership of social network/structure (Portes, 1998)). Social capital typically consists of a social network (e.g. structure for exchange of goods and support), norms (e.g. values, rules etc. in a social group) and sanctions (e.g., motivation to offer social support) (Halpern, 2005; Aßheuer, et al. 2012).

- Expansion of vulnerability in terms of resilience. Resilience was the least developed determinant of vulnerability compared with exposure and sensitivity, and it is therefore recommended that additional research is undertaken to identify other suitable components of resilience. These could be related to adaptation, i.e., medium- and/or long-term reorganisation, changes in institutions (such as relevant policy to support more budget distribution for rural road maintenance and drainage widening).

9.2.2 Recommendation for further work

The following recommendations are suggested to improve the developed methodology.

- This study stated that the more assets a rural community can mobilise implies the stronger coping capacity the community has to deal with the impact from exposure. However, the study fails to consider (a.) the specific immediate coping measures based on the availability of assets and (b.) the degree to which such measures could eliminate the exposure impacts. Further research could include such consideration through improving the methodology developed in the Chapter 4.
- This study used additive formulas (see Eq. 5-6, Eq. 5-7 and Eq. 5-20) to calculate exposure, sensitivity and resilience, and develop a single layer vulnerability reasoning model. This model included a collection of rules with respect to the relationship between exposure, sensitivity and resilience, and vulnerability. Through such rules, the vulnerability can be inferred through the calculated exposure, sensitivity and resilience. As such rules are straightforward to understand, further research could utilise the concept of rule to linguistically express the relationship between such as

exposure and its determinants (such as hazardous group, hazardous event). Therefore, the developed methodology could be improved to develop a multi-layer vulnerability reasoning model for vulnerability assessment.

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Appendix A: Fuzzy mathematics

1. ***Fuzzy set***

(1) Basics:

A set on a universe of discourse U which is characterised by a membership function (MF) $\mu_{\tilde{A}}(x)$ whose value is confined to between 0 and 1 is a fuzzy set Ã expressed as follows:

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) | x \in U, \mu_{\tilde{A}}(x) \in [0,1]\}$$

Therefore, a fuzzy set allows partial belongingness of its members. The membership function of the fuzzy set expresses the degree to which a member of a set belongs to the set. $\mu_{\tilde{A}}(x) = 0$ represent x does not completely belong to Ã, while $\mu_{\tilde{A}}(x) = 1$ represents x completely belongs to Ã. Normally, membership function has different shapes, such as triangular, trapezoidal and bell shapes.

Example A-1:

"close to number 10" can be expressed as a fuzzy set $\tilde{A}_{\text{close to number 10}}$:

$$\tilde{A}_{\text{close to number 10}} = \{(6,0)(7,0.2)(8,0.5)(9,0.9)(10,1)(11,0.9)(12,0.5)(13,0.2)(14,0)\}$$

This fuzzy set can be expressed as its triangular membership function in Figure A-1:

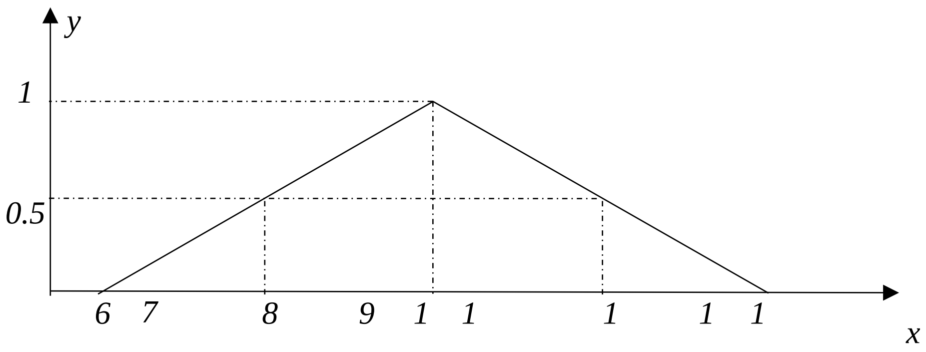

Figure A-1: the membership function of the fuzzy set for "close to number 10"

(2)α-Cut fuzzy set

The α-cut fuzzy set includes members whose membership must be equal and/or greater than α. It is mathematically expressed as follows:

$$\tilde{A}_{\alpha} = \{(x, \mu_{\tilde{A}}(x)) | x \in U, \mu_{\tilde{A}}(x) \geq \alpha\}$$

where α is arbitrary.

Reconsidering the example: A-1, when $\alpha = 0.5$, the fuzzy set of "close to number 10" can be represented as:

$$\tilde{A}_{0.5}^{\text{close to number 10}} = \{8, 9, 10, 11, 12\}$$

2. <u>Fuzzy number</u>

A fuzzy number is a parametric representation of a fuzzy set characterised by a piecewise continuous membership function. Therefore, fuzzy number refers to a real number interval with fuzzy boundary (Bojadziev and Bojacziev, 1997).

3. ***Linguistic variable***

Zadeh (1965) states that the use of linguistic variables whose values are words or sentences in natural language rather than numbers is a natural result when addressing precision under the context of overpowering complexity. Therefore, a linguistic variable is defined as the quintuple:

$$\text{Linguistic variable} = (x, T(x), \mathrm{U}, \mathrm{M})$$

Where x is name of variable, $T(x)$ represents set of linguistic values in which every element can be a value of the variable, U is the universe of discourse of linguistic variable, M expresses semantic rules which map element in $T(x)$ to fuzzy sets in U.

For example, a linguistic variable X can be used to approximately describe height of an adult male, whose name is “HEIGHT”, where

$$\mathrm{X} = (HEIGHT, T(HEIGHT), \mathrm{U}, \mathrm{M})$$

HEIGHT: name of the variable X

$T(HEIGHT)$: $\{tall, medium\ height, low\}$

U: $[0{,}200]$ universe of discourse

$$\mathrm{M}\ (\text{tall}) = \{\left(x, \mu_{\text{medium height}}\ (x)\right) | x \in U\}$$

$$\mu_{\text{medium height}}\ (x) = \begin{cases} \frac{(x-\mathrm{a})}{(\mathrm{b}-\mathrm{a})}, & 100 \le \text{andx} \le 140 \\ 1, & 140 \le \text{andx} \le 160 \\ \frac{(x-d)}{(\mathrm{c}-\mathrm{d})}, & 160 \le \text{andx} \le 180 \\ 0, & \text{otherwise} \end{cases}$$

Appendix B: A brief description of MYCIN

The MYCIN is based on CF (see Section 3.4.2.2.1 in Chapter 3) and includes several major components as described below.

1. ***Expression of the uncertainty of a rule***

In general, "uncertain rule" refers to an uncertain association between evidence and a hypothesis in the following form: IF (antecedent) … THEN (consequent), as symbolised by $E \rightarrow H$ (Durkin, 1994). MYCIN contains several uncertain rules (Shortliffe and Buchanan, 1985). For example, some rules reflect an uncertain relationship between a symptom and an illness, as a particular symptom may correspond to several illnesses. This situation causes the rule to imply a specific illness with uncertainty from a specific symptom.

MYCIN utilises CF to characterise the uncertainty (or creditability) of the rule numerically. Briefly,

(1) $\mathrm{CF} = 1$ and $\mathrm{CF} = -1$ respectively represent the absolute belief (or confirmation) and the absolute disbelief (or disconfirmation) for the rule.

(2) $0 < \mathrm{CF} < 1$ and $-1 < \mathrm{CF} < 0$ respectively represent the partial belief and the partial disbelief for the rule.

(3) $\mathrm{CF} = 0$ represents no idea (or ignorance) of the rule.

Furthermore, $\mathrm{CF}\,(\mathrm{H}, \mathrm{E})$ represents H's degree of belief due to the presence of E (Adam, 1985; Liu et al., 2016).

2. ***Expression of uncertainty of evidence***

According to Shortliffe and Buchanan (1985), "uncertainty of evidence" refers to judgement regarding a fact that is unable to completely match for the antecedent part of the rule. For example, given rule 1 "if the apple is red, then the apple is sweet", when a judgement is made on the probability of "the apple is red" that is less than 1, this judgement is referred to as uncertain evidence for rule 1. Hence, such judgement can lead to an uncertain conclusion; that is, "the apple is sweet" is not certain. If the uncertain conclusion is then used as evidence in another rule, the uncertain conclusion is considered to be uncertain evidence. For instance, given rule 2 "if the apple is sweet, then it can sell for a good price", the uncertain conclusion in rule 1 – which is now considered to be uncertain evidence in rule 2 – leads to an uncertain conclusion for rule 2. That is, "it can sell for a good price" is uncertain.

The CF (E, e) term is utilised to express the degree to which a judgement e supports or does not support E (i.e., the belief for E or the disbelief for E, based on e). Specifically,

(1) CF $(E, e) = 1$ indicates that e absolutely supports E;

(2) $0 <$ CF $(E, e) < 1$ means partial support;

(3) CF $(E, \mathrm{e}) = -1$ means total non-support;

(4) $-1 <$ CF $(E, \mathrm{e}) < 0$ means partial non-support;

(5) CF $(E, e) = 0$ shows the mutual independence of e and E.

"Independence" refers to whether the presence or absence of an element has any implication for another element (Bertsekas and Tsitsiklis, 2000). Therefore, the presence of e does not provide any information for E; i.e., CF $(E, e) = 0$.

3. <u>CF-based uncertainty logical operations</u>

According to Liu et al. (2016), if a rule consists of n evidences E_n in its antecedent part and has n uncertain judgements e_n corresponding to E_n, then the CF-based logical operations of conjunction, disjunction and negation are performed as follows:

(1) Given a rule, its antecedent part is $E = E_1 \ and \ E_2 \ and \ E_3 \ and \ ... \ E_n$, with the assumption of mutual independence of $E_1, E_2, E_3, ..., E_n$. If $\mathrm{CF}(E_1, e_1)$, $\mathrm{CF}(E_2, e_2)$, $\mathrm{CF}(E_3, e_3)$,…, $\mathrm{CF}(E_n, e_n)$ are known, then:

$$\mathrm{CF}(E, e) = \min\{CF(E_1, e_1), CF(E_2, e_2), CF(E_3, e_3), ..., CF(E_n, e_n)\} \qquad Eq. B - 1$$

(2) Given a rule, its antecedent part is $E = E_1 \ or \ E_2 \ or \ E_3 \ or \ ... \ E_n$ with the assumption of mutual independence of $E_1, E_2, E_3, ..., E_n$. If $\mathrm{CF}(E_1, e_1)$, $\mathrm{CF}(E_2, e_2)$, $\mathrm{CF}(E_3, e_3)$,…, $\mathrm{CF}(E_n, e_n)$ are known, then:

$$\mathrm{CF}(E, e) = \max\{\mathrm{CF}(E_1, e_1), \mathrm{CF}(E_2, e_2), \mathrm{CF}(E_3, e_3), ..., \mathrm{CF}(E_n, e_n)\} \qquad Eq. B - 2$$

(3) Given an E, its negation (i.e., not E) is expressed as:

$$- \mathrm{CF}\ (E, e) \qquad Eq. B - 3$$

4. Inference process

In MYCIN (Shortliffe and Buchanan, 1975), there are two kinds of MP-based inference processes. The first process is that more than one piece of evidence contributes to the same hypothesis, which is referred to as "parallel combination". A parallel-combination-related inference network is shown in Figure 3-4:

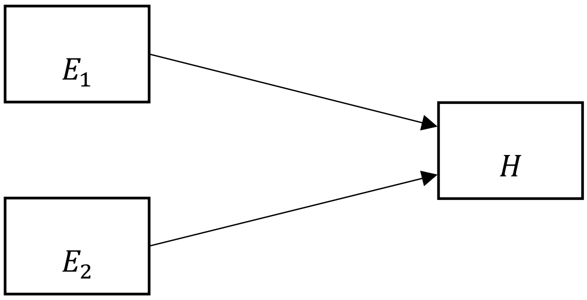

Figure B-1: Inference network related to parallel combination (source: Heckerman, 1990)

MYCIN sets a threshold for creditability of rules. If the creditability of a rule is greater than or equal to 0.2 (i.e., CF $\geq$ 0.2), this rule can be employed. Assuming two rules, rule 1 (denoted $E_1 \rightarrow$ H), rule 2 ($E_2 \rightarrow$ H), and E_1andE_2 are fully independent.

Given CF $(E_1, e_1) \geq 0.2$ and CF $(E_2, e_2) \geq 0.2$, this means evidence E_1 and E_2 supported by the relevant judgements e_1 and e_2 are valid to infer H. Therefore, as suggested by Liu et al. (2016), H, which can be inferred by e_1 and e_2, is represented via: CF $(\mathrm{H}, e_1) =$ CF $(E_1, e_1) \times$ CF (H, E_1) and CF $(\mathrm{H}, e_2) =$ CF $(E_2, e_2) \times$ CF (H, E_2). Here, CF (H, E_1) and CF (H, E_2) represent the creditability of rule 1and2, and CF $(\mathrm{H}, E_1) \geq 0.2$ and CF $(\mathrm{H}, E_2) \geq$ 0.2.

According to Heckerman (1990) and Liu et al. (2016), the parallel-combination kind of inference, namely CF $(\mathrm{H}, e_1$and$e_2)$, can be calculated as follows:

$$\begin{cases} \mathrm{CF}\ (\mathrm{H}, e_1) + \mathrm{CF}\ (\mathrm{H}, e_2) - \mathrm{CF}\ (\mathrm{H}, e_1) \times \mathrm{CF}\ (\mathrm{H}, e_2), & \text{if CF}\ (\mathrm{H}, e_1) \geq 0\ and\ \mathrm{CF}\ (\mathrm{H}, e_2) \geq 0; \\ \mathrm{CF}\ (\mathrm{H}, e_1) + \mathrm{CF}\ (\mathrm{H}, e_2) - \mathrm{CF}\ (\mathrm{H}, e_1) \times \mathrm{CF}\ (\mathrm{H}, e_2), & \text{if CF}\ (\mathrm{H}, e_1) \leq 0\ and\ \mathrm{CF}\ (\mathrm{H}, e_2) \leq 0; \\ 0, & \text{if CF}\ (\mathrm{H}, e_1) \times \mathrm{CF}\ (\mathrm{H}, e_2) < 0\ and\ |\mathrm{CF}\ (\mathrm{H}, e_1) \times \mathrm{CF}\ (\mathrm{H}, e_2)| = 1; \\ \dfrac{\mathrm{CF}\ (\mathrm{H}, e_1) + \mathrm{CF}\ (\mathrm{H}, e_2)}{1 - \min\{|CF\ (H, e_1)|, |\mathrm{CF}\ (\mathrm{H}, e_2)|\}}, & \text{if CF}\ (\mathrm{H}, e_1) \times \mathrm{CF}\ (\mathrm{H}, e_2) < 0\ and\ |\mathrm{CF}\ (\mathrm{H}, e_1) \times \mathrm{CF}\ (\mathrm{H}, e_2)| \neq 1; \end{cases} \quad Eq. B-4$$

If the result of CF (H, $e_1$ande_2) is a positive number, the increase in the degree of belief for hypothesis H is given by $e_1$ande_2. If the result of CF (H, $e_1$ande_2) is a negative number, it indicates the increase in disbelief degree of hypothesis H given by $e_1$ande_2.

The second process is that a hypothesis is treated as evidence for another hypothesis; this is referred to as sequential combination. A sequential-combination-related inference network is diagrammed as Figure 3-5 and is a parallel-combination-related inference network.

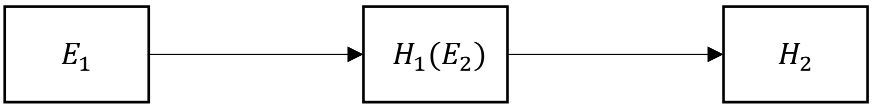

Figure B-2: Sequential combination related inference network (source: Heckerman, 1990)

Two rules are given, namely rule 1, denoted $E_1 \rightarrow H_1$, and rule 2, denoted $E_2 \rightarrow H_2$. Here, H_1 is the hypothesis in rule 1, which is viewed as the evidence E_2 in rule 2. When rule 1 receives a judgement e_1 and CF $(E_1, e_1) \geq 0.2$, then CF $(H_1, e_1) =$ CF $(E_1, e_1) \times$ CF (H_1, E_1). Then, CF$(H_2, E_2(H_1))$ = CF $(H_1, e_1) \times$ CF (H_2, E_2) if CF $(H_1, e_1) \geq 0.2$. If the result of CF(H_2, H_1) is a positive number, it means the increase in belief degree for hypothesis H_2 given by H_1. If the result of CF(H_2, H_1) is a negative number, it indicates the increase in disbelief degree for hypothesis H_2 that is given by H_1.

5. ***Certainty factor model***

As described in Chapter 3, the way to calculate CF was suggested (see Eq. 3-6). Further to the calculation of MB and MD in CF is demonstrated below.

Mathematically, MB (H, E) and MD (H, E) can be clculated as follows:

$$\text{MB }(H, E) = \text{MB }(H|E) = \begin{cases} 1, & if\ P(H) = 1 \\ \dfrac{\max[P(H|E), P(H)] - P(H)}{\max[0,1] - P(H)}, & otherwise \end{cases} \qquad Eq. B - 5$$

$$\text{MD }(H, E) = \text{MD }(H|E) = \begin{cases} 1, & if\ P(H) = 0 \\ \dfrac{\min[P(H|E), P(H)] - P(H)}{\min[0,1] - P(H)}, & otherwise \end{cases} \qquad Eq. \text{B} - 6$$

Here, $P(H)$ is the prior probability of the occurrence of H; $P(H|E)$ is the posterior probability (or update probability) based on the occurrence of E; $\max[P(H|E), P(H)] - P(H)$ is the increase in $P(H)$ in light of $P(H|E)$ based on E; and $\max[0,1] - P(H)$ is the probability of non-occurrence of H. Hence, $\frac{\max[P(H|E), P(H)] - P(H)}{\max[0,1] - P(H)}$, which is an absolute increase in probability of H due to the presence of E, refers to the relative increase in belief degree for H based on E. Hence, $\frac{\min[P(H|E), P(H)] - P(H)}{\min[0,1] - P(H)}$ refers to the relative increase in disbelief degree for H based on E.

Appendix C: A brief description of PROSPECTOR

PROSPECTOR takes advantage of Bayesian theorem (see Section 3.4.2.2.2) and it includes several major components as below.

1. __Preliminary__

Based on this, $P(A)$ and $P(B)$ respectively correspond the probability of an evidence (denoted as $P(E)$) and the probability of a hypothesis (denoted as $P(H)$). As suggested by (Webber and Nilsson, 1981), if the evidence is present, Eq.3-7 is transformed into equations C-1 and C-2. These both lead to equation C-3, as follows:

$$\mathrm{P}(H|E) = \frac{P(E|H) \times P(H)}{P(E)} \qquad Eq.C-1$$

$$\mathrm{P}(\overline{H}|E) = \frac{P(E|\overline{H}) \times P(\overline{H})}{P(E)} \qquad Eq.C-2$$

$$\frac{P(H|E)}{P(\overline{H}|E)} = \frac{P\ (E|H) \times P(H)}{P\ (E|\overline{H}) \times P(\overline{H})} \qquad Eq.C-3$$

where $P(E)$ is the probability of the presence of evidence (denoted as E); $P(H)$ is the probability of a hypothesis H; $P\ (E|H)$ is the probability of E based on H; $P(E|\overline{H})$ is the probability of E based on $\overline{H}$ (denoting the negation of H); $P(H|E)$ is the probability of H based on E; and $\mathrm{P}(\overline{H}|E)$ is the probability of $\overline{H}$ based on E.

Therefore, $\frac{P(H)}{P(\overline{H})}$ is the relative probability of H compared with $\overline{H}$; i.e., the prior probability.

The $\frac{P\ (E|H)}{P\ (E|\overline{H})}$ term is the relative probability of E when based on H, compared with E based on $\overline{H}$, and expresses the sufficiency of E for implying H. Thus, $\frac{P\,(E|H)}{P\left(E\middle|\overline{H}\right)}$ could be considered an indicator of the strength of a rule in terms of sufficiency; that is, the degree to which the presence of the evidence is sufficient to support the hypothesis. Hence, Eq. C-3 expresses an inference process for updating priori probability ($\frac{P(H)}{P(\overline{H})}$) into posterior probability ($\frac{P(H|E)}{P\left(\overline{H}\middle|E\right)}$ using new information ($\frac{P\,(E|H)}{P\left(E\middle|\overline{H}\right)}$). It represents the relative probability of H compared with $\overline{H}$ based on E.

If the evidence is absent, Eq.3-7 (see Chapter 3) is transformed into equations C-4 and C-5. Both of them lead to equation C-6, as follows:

$$\mathrm{P(H}|\bar{E}) = \frac{P\;(\bar{E}|H)\;\times\;P(H)}{P(\bar{E})} \qquad Eq.C-4$$

$$\mathrm{P}(\overline{H}|\bar{E}) = \frac{P\;(\bar{E}|\overline{H})\;\times\;P(\overline{H})}{P(\bar{E})} \qquad Eq.C-5$$

$$\frac{P(H|\bar{E})}{P\left(\overline{H}\middle|\bar{E}\right)} = \frac{P\;(\bar{E}|H)\;\times\;P(H)}{P\;\left(\bar{E}\middle|\overline{H}\right)\;\times\;P(\overline{H})} \qquad Eq.C-6$$

where $P(\bar{E})$ is the probability of the absence of evidence (denoted as $\bar{E}$); $P\;(\bar{E}|H)$ is the probability of the $\bar{E}$ based on H; $\mathrm{P(H}|\bar{E})$ is the probability of H based on $\bar{E}$; $P\;(\bar{E}|\overline{H})$ is the probability of $\bar{E}$ based on $\overline{H}$; and $\mathrm{P}(\overline{H}|\bar{E})$ is the probability of the $\overline{H}$ based on $\bar{E}$.

Therefore, $\frac{P\left(\bar{E}\middle|H\right)}{P\left(\bar{E}\middle|\overline{H}\right)}$ is the relative probability of $\bar{E}$ based on H compared with based on $\overline{H}$; this value expresses the necessity of E for implying H. Hence, $\frac{P\left(\bar{E}\middle|H\right)}{P\left(\bar{E}\middle|\overline{H}\right)}$ could be considered an indicator of the strength of a rule in terms of necessity; that is, the degree to which the presence of the evidence is necessary to support the hypothesis. Accordingly, Eq. C-6 expresses an inference process of updating a priori probability ($\frac{P(H)}{P(\overline{H})}$) into a posterior probability ($\frac{P(H|\bar{E})}{P(\overline{H}|\bar{E})}$, representing the relative probability of H based on $\bar{E}$ compared with $\overline{H}$ based on $\bar{E}$) using new information ($\frac{P(\bar{E}|H)}{P(\bar{E}|\overline{H})}$).

2. Uncertainty expression

2.1 Expression of uncertainty of rule

PROSPECTOR consists of a series of rules. As each rule expresses an inexact association between the evidence of a kind of mineral observed and a hypothesis of the existence of another mineral, this association is also called the uncertainty of a rule. Duda et al. (1981) designed a sufficiency measure (LS) and necessity measure (LN) to represent this uncertainty. The LS and LN are generally expressed as a probability, particularly as a likelihood rather than the frequency where refers to an approximate expression of probability of the occurrence of an event. Exploring a new prospect site is not a repetitive event; hence, frequency is inappropriate for representing the probability of such an activity. Duda et al. (1976) also identified the viability of subjective probability as an alternative to likelihood. Consequently, LS is measured as a likelihood ratio using Eq.C-7 as follows:

$$\mathrm{LS} = \frac{P(E|H)}{P(E|\overline{H})} = \mathrm{O}(E|H) \qquad Eq.\mathrm{C}-7$$

where $P(E|H)$ is the likelihood of E based on H, and $P(E|\overline{H})$ is the likelihood of E without H (or based on $\overline{H}$). Therefore, the ratio of $P(E|H)$ to $P(E|\overline{H})$ represents the relative likelihood of E based on H, compared to E based on $\overline{H}$; that is, the odds of E based on H compared with based on $\overline{H}$, shown as $O(E|H)$. The higher the ratio, the more sufficient E is to imply H and the higher the creditability of a rule.

LN is measured by a likelihood ratio calculated as follows:

$$LN = \frac{P(\overline{E}|H)}{P(\overline{E}|\overline{H})} = O(\overline{E}|H) \qquad Eq.\text{C} - 8$$

where $P(\overline{E}|H)$ is the likelihood of $\overline{E}$ based on H, whereas $P(\overline{E}|\overline{H})$ is the likelihood of $\overline{E}$ based on $\overline{H}$. Therefore, the ratio of $P(\overline{E}|H)$ to $P(\overline{E}|\overline{H})$ means the relative likelihood of $\overline{E}$ based on H (versus based on $\overline{H}$); that is, the odds of $\overline{E}$ based on H compared with based on $\overline{H}$, written as $O(\overline{E}|H)$. The lower the ratio, the more necessary E is to imply H and the higher the creditability of the rule.

Specifically, LS and LN range from zero to infinity. If $LS \gg 1$, it means that E is favourable for H. This implies that $\overline{E}$ is unfavourable for H, which can be written as $0 < LN \ll 1$. Therefore, E that is sufficient to imply H. When LS approaches infinity, it means that E is ample to imply H. If $0 < LS \ll 1$, the E is unfavourable for H. This means $\overline{E}$ is encouraging for H, or $LN \gg 1$. Therefore, E that is insufficient to imply H is unnecessary to imply H. When LN approaches infinity, $\overline{E}$ is adequate to imply H. If $LS = 1$, there is no relationship between E and H. This implies there is no relationship between $\overline{E}$ and H; that is, $LN = 1$. If $LS = 0$, it means that the presence of E implies a false H, whereas $LN = 0$, E is logically necessary for H.

2.2 Expression of uncertainty of evidence

The uncertainty of evidence is measured by the likelihood of the occurrence of the evidence (Duda et al., 1976). For example, if an expert makes a judgement that E is true with 60% certainty, the expert means that $\mathrm{P}(E|\, judgement) = 0.6$. Here, e represents a judgement; that is, $\mathrm{P}(E|e) = 0.6$. Accordingly, $\mathrm{P}(E|e) = 0$ represents the judgement of e that implies that the likelihood of E occurring is 0%, while $\mathrm{P}(E|e) = 1$ represents the judgement that the likelihood of the occurrence of E is 100%. Both scenarios are extreme cases of uncertain evidence.

It is difficult to obtain the likelihood of evidence for certain occasions in a specific application. Hence, PROSPECTOR takes advantage of a certainty scale or belief degree between -5 and 5 to alternatively represent the likelihood of the evidence (Duda et al., 1981). For three extreme cases,

(1.) $\mathrm{C}(E|e) = -5$ represents the likelihood of E being zero given e; that is, $\mathrm{P}(E|\mathrm{e}) = 0$;

(2.) $\mathrm{C}(E|e) = 5$ represents the likelihood of E being 1 given e; that is, $\mathrm{P}(E|\mathrm{e}) = 1$;

(3.) $\mathrm{C}(E|e) = 0$ represents the mutual independence of E and e; that is, $\mathrm{P}(E|\mathrm{e}) = P(E)$.

For the remainder of the certainty values, a piecewise linear function is established for mapping certainty scores into probability values (Duda et al., 1981). The process is mathematically demonstrated as follows:

$$\mathrm{P}(E|e) = \begin{cases} \dfrac{\mathrm{C}(E|e) + \mathrm{P}(E) \times (5 - \mathrm{C}(E|e))}{5}, & if \;\; 0 \ll \mathrm{C}(E|e) \ll 5 \\ \dfrac{P(E) \times (\mathrm{C}(E|e) + 5)}{5}, & if -5 \ll \mathrm{C}(E|e) \ll 0 \end{cases} \qquad Eq. C-9$$

3. ***Uncertainty logical operations of conjunction, disjunction and negation***

According to Duda et al. (1976), conjunction, disjunction and negation operations are described as follows:

(1) Conjunction: assume the mutual independence of $E_1\ and\ E_2\ and\ E_3\ and\ ...\ E_n$. If the rule's antecedent part is $E = E_1\ and\ E_2\ and\ E_3\ and\ ...\ E_n$, and $P(E_1|e_1)$, $P(E_2|e_2)$, $P(E_3|e_3)$,…, $P(E_n|e_n)$ are known, then:

$$P(E|e) = P(E_1 \cap E_2 \cap E_3 \cap ... \cap E_n|e_n) = \prod_{i=1}^{n} P(E_i|e_i) \qquad Eq.C-10$$

(2) Disjunction: assume the mutual independence of $E_1\ and\ E_2\ and\ E_3\ and\ ...\ E_n$. If the rule's antecedent part is $E = E_1\ or\ E_2\ or\ E_3\ or\ ...\ E_n$, and $P(E_1|e_1)$, $P(E_2|e_2)$, $P(E_3|e_3)$,…, $P(E_n|e_n)$ are known, then:

$$P(E|e) = P(E_1 \cup E_2 \cup E_3 \cup ... \cup E_n|e_n) = 1 - \prod_{i=1}^{n}[1 - P(E_i|e_i)] \qquad Eq.C-11$$

(3) Negation: $P(\bar{E}|e) = 1 - P(E|e)$ $\qquad Eq.C-12$

4. ***Certain and uncertain inference processes***

4.1 Inference processes with certain evidence

Duda et al. (1976) proposed inference processes through using certain evidence, which consists of certainly true evidence E (i.e. $P(E) = 1$) and certainly false evidence $\overline{E}$ (i.e. $P(\overline{E}) = 0$). When the judgement of E is known to be certainly true, the given prior odds for hypothesis $H, namely\ O(H)$, can be updated to be posterior odds, namely $O(H|E)$. This is done by considering only the LS of the rule, mathematically demonstrated, in light of Eq.C-3 as follows:

$$\mathrm{O(H|E)} = LS \times O\,(H) \qquad Eq.C-13$$

in which $O\,(H)$ is the ratio of likelihood for the occurrence of H to the likelihood of non-occurrence of H (signified as $\overline{H}$). Alternatively, to the extent that the likelihood and odds are interchangeable – that is, $\mathrm{O(H|E)} = \frac{P(H|E)}{P(H|\overline{E})} = \frac{P(H|E)}{1-P(H|E)}$, the result of this inference process can be represented by likelihood, as follows:

$$\mathrm{P(H}|E) = \frac{O(H|E)}{1+O(H|E)} = \frac{LS \times P(H)}{(LS-1) \times P(H)+1} \qquad Eq.C-14$$

When E is known to be certainly false, signified as $\mathrm{P}\left(\overline{E}\right) = 0$, the given prior odds for hypothesis $H, namely\ O(H)$, can be updated to be posterior odds, $\mathrm{O}\left(\mathrm{H}\middle|\overline{E}\right) = \frac{P(H|\overline{E})}{P(\overline{H}|\overline{E})}$. This is done by considering only LN, mathematically demonstrated in light of Eq.C-6 as follows:

$$\mathrm{O}\left(\mathrm{H}\middle|\overline{E}\right) = LN \times O(H) \qquad Eq.C-15$$

Alternatively, since $\mathrm{O}\left(\mathrm{H}\middle|\overline{E}\right) = \frac{P(H|\overline{E})}{1-P(H|\overline{E})}$, the result of this inference process can be represented as the likelihood, as follows:

$$\mathrm{P}\left(\mathrm{H}\middle|\overline{E}\right) = \frac{O(H|\overline{E})}{1+O(H|\overline{E})} = \frac{LN \times P(H)}{(LN-1) \times P(H)+1} \qquad Eq.C-16$$

4.2 <u>Inference processes with uncertain evidence</u>

Duda et al. (1976) also proposed inference processes using uncertain evidence E, employing the equation as follows:

$$\mathrm{P(H}|e) = P(H|E) \times P(E|e) + P\left(H\middle|\overline{E}\right) \times P\left(\overline{E}\middle|e\right) \qquad Eq.C-17$$

Specifically, the equation is transformed into four types of variances in four scenarios. The first scenario is that E is absolutely true given the judgement e; that is, $P(E|e) = 1$. Hence, $P(\overline{E}|e) = 0$, so that $\mathrm{P}(H|e) = P(H|E)$. The second scenario is that E is absolutely false given the judgement e; that is, $P(\overline{E}|e) = 1$. Hence, $P(E|e) = 0$, so that $\mathrm{P}(\mathrm{H}|e) = \mathrm{P}(H|\overline{E})$. The third scenario is the mutual independence of E and e; that is, $P(E|e) = 0$; therefore, $\mathrm{P}(H|e) = P(H)$. The fourth scenario is as follows:

$$\mathrm{P}(H|e) = \begin{cases} P(H|\overline{E}) + \dfrac{\mathrm{P}(H) - P(H|\overline{E})}{P(E)} \times P(E|e), & if \ 0 \leq \mathrm{P}(E|e) \leq P(E) \\ P(H) + \dfrac{P(H|E) - P(H)}{1 - P(E)} \times [P(E|e) - P(E)], & if P(E) \leq \mathrm{P}(E|e) \leq 1 \end{cases} \quad Eq. C-18$$

When $P(E|e)$ cannot be obtained, the equation above is equivalent to the following:

$$\mathrm{P}(H|e) = \begin{cases} P(H|\overline{E}) + [\mathrm{P}(H) - P(H|\overline{E})] \times \left[\dfrac{1}{5} C(E|e) + 1\right], & if \ \mathrm{C}(E|e) \leq 0 \\ P(H) + [P(H|E) - P(H)] \times \left[\dfrac{1}{5} C(E|e)\right], & if \ \mathrm{C}(E|e) > 0 \end{cases} \quad Eq. C-19$$

Appendix D: Expert opinions on pair-wise comparison

Exposure

<u>Rural road manager 1:</u>

Exposure	Agriculture	Education	Employment	Health	Income and	Marketing
Agriculture	(1, 1, 1, 2)	(4, 5, 5 ,6)	(1/2, 1/3, 1/3, 1/4)	(1/5, 1/6, 1/6, 1/7)	(3, 4, 4, 5)	(1, 2, 2, 3)
Education	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(1/4, 1/5, 1/5, 1/6)	(1/2, 1/3, 1/3, 1/4)	(1/3, 1/4, 1/4, 1/5)
Employment	(2, 3, 3, 4)	(2, 3, 3, 4)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(4, 5, 5 ,6)	(2, 3, 3, 4)
Health	(5, 6, 6, 7)	(4, 5, 5 ,6)	(3, 4, 4, 5)	(1, 1, 1, 2)	(5, 6, 6, 7)	(4, 5, 5 ,6)
Income and consumption	(1/3, 1/4, 1/4, 1/5)	(2, 3, 3, 4)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)
Marketing	(1, 1/2, 1/2, 1/3)	(3, 4, 4, 5)	(1/2, 1/3, 1/3, 1/4)	(1/4, 1/5, 1/5, 1/6)	(2, 3, 3, 4)	(1, 1, 1, 2)

Agriculture	The transportation of tobacco leaf	The transportation of water/fertilizer for irrigation/fertilization	The transportation of grass for feeding animals (e.g. pigs)	The extension worker's visit

The transportation of tobacco leaf	(1,1,1,2)	(1/2, 1/3, 1/3, 1/4)	(1/4, 1/5, 1/5, 1/6)	(4, 5, 5 ,6)
The transportation of water/fertilizer for irrigation/fertilization	(2, 3, 3, 4)	(1,1,1,2)	(1/2, 1/3, 1/3, 1/4)	(4, 5, 5 ,6)
The transportation of grass for feeding animals (e.g. pigs)	(4, 5, 5 ,6)	(2, 3, 3, 4)	(1,1,1,2)	(5, 6, 6, 7)
The extension worker's visit	(1/4, 1/5, 1/5, 1/6)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1,1,1,2)

Education	The access to school	The health educator’s visiting	Labour training
The access to school	(1,1,1,2)	(5, 6, 6, 7)	(1/3, 1/4, 1/4, 1/5)
The health educator’s visiting	(1/5, 1/6, 1/6, 1/7)	(1,1,1,2)	(1/7, 1/8, 1/8, 1/9)
Labour training	(3, 4, 4, 5)	(7, 8, 8, 9)	(1,1,1,2)

Employment	Employee attendance	The access to perform the traditional marriage	The access to perform the traditional funeral	The potential opportunities to be employed

Employee attendance	(1,1,1,2)	(5, 6, 6, 7)	(5, 6, 6, 7)	(2, 3, 3, 4)
The access to perform the traditional marriage	(1/5, 1/6, 1/6, 1/7)	(1,1,1,2)	(1,1,1,2)	(1/3, 1/4, 1/4, 1/5)
The access to perform the traditional funeral	(1/5, 1/6, 1/6, 1/7)	(1,1,1,2)	(1,1,1,2)	(1/3, 1/4, 1/4, 1/5)
The potential opportunities to be employed	(1/2, 1/3, 1/3, 1/4)	(3, 4, 4, 5)	(3, 4, 4, 5)	(1,1,1,2)

Health	Buying medication	Emergency service	The access to health centres	The access to maternity centres	The immunisation programs
Buying medication	(1,1,1,2)	(1/8, 1/9, 1/9, 1/9)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)	(1/3, 1/4, 1/4, 1/5)
Emergency service	(8, 9, 9, 9)	(1,1,1,2)	(6, 7, 7, 8)	(4, 5, 5 ,6)	(7, 8, 8, 9)
The access to health centres	(6, 7, 7, 8)	(1/6, 1/7, 1/7, 1/8)	(1,1,1,2)	(1/2, 1/3, 1/3, 1/4)	(3, 4, 4, 5)
The access to maternity centres	(7, 8, 8, 9)	(1/4, 1/5, 1/5, 1/6)	(2, 3, 3, 4)	(1,1,1,2)	(4, 5, 5, 6)

The immunisation programs	(3, 4, 4, 5)	(1/7, 1/8, 1/8, 1/9)	(1/3, 1/4, 1/4, 1/5)	(1/4, 1/5, 1/5, 1/6)	(1,1,1,2)

Income and consumption	Buying poultry (e.g. chicken)	Acquisition of photo service	Buying coals	Buying foods and other things used in home	The selling and buying capacities	The standard of living
Buying poultry (e.g. chicken)	(1,1,1,2)	(1, 2, 2, 3)	(1/4, 1/5, 1/5, 1/6)	(1/2, 1/3, 1/3, 1/4)	(1/6, 1/7, 1/7, 1/8)	(1/6, 1/7, 1/7, 1/8)
Acquisition of photo service	(1, 1/2, 1/2, 1/3)	(1, 1, 1, 2)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)	(1/8, 1/9, 1/9, 1/9)	(1/8, 1/9, 1/9, 1/9)
Buying coals	(4, 5, 5, 6)	(6, 7, 7, 8)	(1, 1, 1, 2)	(1, 2, 2, 3)	(1/3, 1/4, 1/4, 1/5)	(1/3, 1/4, 1/4, 1/5)
Buying foods and other things used in home	(2, 3, 3, 4)	(7, 8, 8, 9)	(1,1/2, 1/2, 1/3)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(2, 3, 3, 4)
The selling and buying capacities	(6, 7, 7, 8)	(8, 9, 9, 9)	(3, 4, 4, 5)	(2, 3, 3, 4)	(1, 1, 1, 2)	(1, 1, 1, 2)
The standard of living	(6, 7, 7, 8)	(8, 9, 9, 9)	(3, 4, 4, 5)	(2, 3, 3, 4)	(1, 1, 1, 2)	(1, 1, 1, 2)

Marketing	The access to trading centres	Potential trading opportunities
The access to trading centres	(1,1,1,2)	(5, 6, 6, 7)
Potential trading opportunities	(1/5, 1/6, 1/6, 1/7)	(1,1,1,2)

Rural road manager 2:

Exposure	Agriculture	Education	Employment	Health	Income and	Marketing
Agriculture	(1, 1, 1, 2)	(1, 2, 2, 3)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(5, 6, 6, 7)	(6, 7, 7, 8)
Education	(1, 1/2, 1/2, 1/3)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/7, 1/8, 1/8, 1/9)	(1/3, 1/4, 1/4, 1/5)	(1/2, 1/3, 1/3, 1/4)
Employment	(4, 5, 5 ,6)	(4, 5, 5 ,6)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(4, 5, 5 ,6)	(1/2, 1/3, 1/3, 1/4)
Health	(6, 7, 7, 8)	(7, 8, 8, 9)	(5, 6, 6, 7)	(1, 1, 1, 2)	(6, 7, 7, 8)	(7, 8, 8, 9)
Income and consumption	(1/5, 1/6, 1/6, 1/7)	(3, 4, 4, 5)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)
Marketing	(1/6, 1/7, 1/7, 1/8)	(2, 3, 3, 4)	(2, 3, 3, 4)	(1/7, 1/8, 1/8, 1/9)	(4, 5, 5 ,6)	(1, 1, 1, 2)

Agriculture	The transportation of tobacco leaf	The transportation of water/fertilizer for irrigation/fertilization	The transportation of grass for feeding animals (e.g. pigs)	The extension worker's visit
The transportation of tobacco leaf	(1, 1, 1, 2)	(/15, 1/6, 1/6, 1/7)	(1/4, 1/5, 1/5, 1/6)	(3, 4, 4, 5)
The transportation of water/fertilizer for irrigation/fertilization	(5, 6, 6, 7)	(1, 1, 1, 2)	(3, 4, 4, 5)	(6, 7, 7, 8)
The transportation of grass for feeding animals (e.g. pigs)	(4, 5, 5, 6)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)	(5, 6, 6, 7)
The extension worker's visit	(1/3, 1/4, 1/4, 1/5)	(1/6, 1/7, 1/7, 1/8)	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)

Education	The access to school	The health educator’s visiting	Labour training
The access to school	(1, 1, 1, 2)	(5, 6, 6, 7)	(1/4, 1/5, 1/5, 1/6)
The health educator’s visiting	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)	(1/7, 1/8, 1/8, 1/9)

Labour training	(4, 5, 5, 6)	(7, 8, 8, 9)	(1, 1, 1, 2)

Employment	Employee attendance	The access to perform the traditional marriage	The access to perform the traditional funeral	The potential opportunities to be employed
Employee attendance	(1, 1, 1, 2)	(4, 5, 5, 6)	(5, 6, 6, 7)	(3, 4, 4, 5)
The access to perform the traditional marriage	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(1, 1/2, 1/2, 1/3)	(1/3, 1/4, 1/4, 1/5)
The access to perform the traditional funeral	(1/5, 1/6, 1/6, 1/7)	(1, 2, 2, 3)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)
The potential opportunities to be employed	(1/3, 1/4, 1/4, 1/5)	(3, 4, 4, 5)	(4, 5, 5, 6)	(1, 1, 1, 2)

Health	Buying medication	Emergency service	The access to health centres	The access to maternity centres	The immunisation programs

Buying medication	(1, 1, 1, 2)	(1/8, 1/9, 1/9, 1/9)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)	(1/3, 1/4, 1/4, 1/5)
Emergency service	(8, 9, 9, 9)	(1, 1, 1, 2)	(5, 6, 6, 7)	(4, 5, 5, 6)	(6, 7, 7, 8)
The access to health centres	(5, 6, 6, 7)	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(4, 5, 5, 6)
The access to maternity centres	(6, 7, 7, 8)	(1/4, 1/5, 1/5, 1/6)	(3, 4, 4, 5)	(1, 1, 1, 2)	(5, 6, 6, 7)
The immunisation programs	(3, 4, 4, 5)	(1/6, 1/7, 1/7, 1/8)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)

Income and consumption	Buying poultry (e.g. chicken)	Acquisition of photo service	Buying coals	Buying foods and other things used in home	The selling and buying capacities	The standard of living
Buying poultry (e.g. chicken)	(1, 1, 1, 2)	(3, 4, 4, 5)	(3, 4, 4, 5)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(1/5, 1/6, 1/6, 1/7)
Acquisition of photo service	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)	(1/6, 1/7, 1/7, 1/8)

Buying coals	(1/3, 1/4, 1/4, 1/5)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/3, 1/4, 1/4, 1/5)	(1/2, 1/3, 1/3, 1/4)
Buying foods and other things used in home	(4, 5, 5, 6)	(5, 6, 6, 7)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(1/3, 1/4, 1/4, 1/5)
The selling and buying capacities	(6, 7, 7, 8)	(7, 8, 8, 9)	(3, 4, 4, 5)	(2, 3, 3, 4)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)
The standard of living	(5, 6, 6, 7)	(6, 7, 7, 8)	(2, 3, 3, 4)	(3, 4, 4, 5)	(2, 3, 3, 4)	(1, 1, 1, 2)

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Marketing	The access to trading centres	Potential trading opportunities
The access to trading centres	(1, 1, 1, 2)	(4, 5, 5, 6)
Potential trading opportunities	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)

Rural road manager 3:

Exposure	Agriculture	Education	Employment	Health	Income and consumption	Marketing
Agriculture	(1, 1, 1, 2)	(4,5,5,6)	(2,3,3,4)	(1/5, 1/6, 1/6, 1/7)	(2,3,3,4)	(2,3,3,4)
Education	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)	(1,2,2,3)	(1/3, 1/4, 1/4, 1/5)
Employment	(1/2, 1/3, 1/3, 1/4)	(5,6,6,7)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(6,7,7,8)	(3,4,4,5)
Health	(1/5, 1/6, 1/6, 1/7)	(7,8,8,9)	(3,4,4,5)	(1, 1, 1, 2)	(4,5,5,6)	(5,6,6,7)
Income and consumption	(1/2, 1/3, 1/3, 1/4)	(1,1/2, 1/2, 1/3)	(1/6, 1/7, 1/7, 1/8)	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)
Marketing	(1/2, 1/3, 1/3, 1/4)	(3,4,4,5)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(5,6,6,7)	(1, 1, 1, 2)

Agriculture	The transportation of tobacco leaf	The transportation of water/fertilizer for irrigation/fertilization	The transportation of grass for feeding animals (e.g. pigs)	The extension worker's visit

The transportation of tobacco leaf	(1, 1, 1, 2)	(5, 6, 6, 7)	(4, 5, 5, 6)	(6, 7, 7, 8)
The transportation of water/fertilizer for irrigation/fertilization	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)	(5, 6, 6, 7)	(3, 4, 4, 5)
The transportation of grass for feeding animals (e.g. pigs)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)	(1, 2, 2, 3)
The extension worker's visit	(1/6, 1/7, 1/7, 1/8)	(1/3, 1/4, 1/4, 1/5)	(1, 1/2, 1/2, 1/3)	(1, 1, 1, 2)

Education	The access to school	The health educator’s visiting	Labour training
The access to school	(1, 1, 1, 2)	(5,6,6,7)	(1/7, 1/8, 1/8, 1/9)
The health educator’s visiting	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)	(1/8, 1/9, 1/9, 1/9)
Labour training	(7,8,8,9)	(8,9,9,9)	(1, 1, 1, 2)

Employment	Employee attendance	The access to perform the traditional marriage	The access to perform the traditional funeral	The potential opportunities to be employed
Employee attendance	(1, 1, 1, 2)	(7,8,8,9)	(7,8,8,9)	(2,3,3,4)
The access to perform the traditional marriage	(1/7, 1/8, 1/8, 1/9)	(1, 1, 1, 2)	(1,1,1,2)	(1/6, 1/7, 1/7, 1/8)
The access to perform the traditional funeral	(1/7, 1/8, 1/8, 1/9)	(1, 1, 1, 1/2)	(1, 1, 1, 2)	(1/6, 1/7, 1/7, 1/8)
The potential opportunities to be employed	(1/2, 1/3, 1/3, 1/4)	(6, 7, 7, 8)	(6, 7, 7, 8)	(1, 1, 1, 2)

Health	Buying medication	Emergency service	The access to health centres	The access to maternity centres	The immunisation programs
Buying medication	(1, 1, 1, 2)	(1/8, 1/9, 1/9, 1/9)	(1/4, 1/5, 1/5, 1/6)	(1/8, 1/9, 1/9, 1/9)	(1/4, 1/5, 1/5, 1/6)
Emergency service	(8, 9, 9, 9)	(1, 1, 1, 2)	(5, 6, 6, 7)	(3, 4, 4, 5)	(8, 9, 9, 9)

The access to health centres	(4, 5, 5 ,6)	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(3, 4, 4, 5)
The access to maternity centres	(8, 9, 9, 9)	(1/3, 1/4, 1/4, 1/5)	(2, 3, 3, 4)	(1, 1, 1, 2)	(4, 5, 5 ,6)
The immunisation programs	(4, 5, 5 ,6)	(1/8, 1/9, 1/9, 1/9)	(1/3, 1/4, 1/4, 1/5)	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)

Income and consumption	Buying poultry (e.g. chicken)	Acquisition of photo service	Buying coals	Buying foods and other things used in home	The selling and buying capacities	The standard of living
Buying poultry (e.g. chicken)	(1, 1, 1, 2)	(3, 4, 4, 5)	(2, 3, 3, 4)	(1/2, 1/3, 1/3, 1/4)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)
Acquisition of photo service	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(1/5, 1/6, 1/6, 1/7)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)
Buying coals	(1/2, 1/3, 1/3, 1/4)	(2, 3, 3, 4)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)
Buying foods and other things used in home	(2, 3, 3, 4)	(5, 6, 6, 7)	(4, 5, 5 ,6)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)

The selling and buying capacities	(5, 6, 6, 7)	(5, 6, 6, 7)	(5, 6, 6, 7)	(5, 6, 6, 7)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
The standard of living	(6, 7, 7, 8)	(6, 7, 7, 8)	(6, 7, 7, 8)	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)

Marketing	The access to trading centres	Potential trading opportunities
The access to trading centres	(1, 1, 1, 2)	(3, 4, 4, 5)
Potential trading opportunities	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Sensitivity:

<u>Sociologist 1:</u>

Sensitivity	Investment	Stores	Claims
Investment	(1, 1, 1, 2)	(7,8,8,9)	(5,6,6,7)
Stores	(1/7, 1/8, 1/8, 1/9)	(1, 1, 1, 2)	(3,4,4,5)

Claims	(1/5, 1/6, 1/6, 1/7)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset
Human asset	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/3, 1/4, 1/4, 1/5)
Productive asset	(5, 6, 6, 7)	(1, 1, 1, 2)	(4, 5, 5, 6)
Collective asset	(3, 4, 4, 5)	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female
Total population	(1, 1, 1, 2)	(7, 8, 8, 9)	(3, 4, 4, 5)	(5, 6, 6, 7)	(2, 3, 3, 4)	(6, 7, 7, 8)
Women	(1/7, 1/8, 1/8, 1/9)	(1, 1, 1, 2)	(5, 6, 6, 7)	(4, 5, 5, 6)	(6, 7, 7, 8)	(1/2, 1/3, 1/3,
Elderly	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6,	(1, 1, 1, 2)	(3, 4, 4, 5)	(1/2, 1/3, 1/3, 1/4)	(4, 5, 5, 6)
Children	(1/5, 1/6, 1/6, 1/7)	(1/4, 1/5,	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(4, 5, 5, 6)
Disabled	(1/2, 1/3, 1/3, 1/4)	(1/6, 1/7,	(2, 3, 3, 4)	(5, 6, 6, 7)	(1, 1, 1, 2)	(5, 6, 6, 7)
Female headed household	(1/6, 1/7, 1/7, 1/8)	(2, 3, 3, 4)	(1/4, 1/5, 1/5, 1/6)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)
Cultivated land	(2, 3, 3, 4)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(5, 6, 6, 7)	(3, 4, 4, 5)
Access to rural road	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)
Rural transport service	(1/3, 1/4, 1/4, 1/5)	(2, 3, 3, 4)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service
Transporting passenger service	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)

Transporting cargo service	(4, 5, 5, 6)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1/8, 1/9, 1/9, 1/9)	(1/7, 1/8, 1/8, 1/9)
Motorcycle	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)	(1/6, 1/7, 1/7, 1/8)
Motorised tricycle	(5, 6, 6, 7)	(5, 6, 6, 7)	(1, 1, 1, 2)	(1/7, 1/8, 1/8, 1/9)	(1/6, 1/7, 1/7, 1/8)
Private car	(8, 9, 9, 9)	(7, 8, 8, 9)	(7, 8, 8, 9)	(1, 1, 1, 2)	(4, 5, 5, 6)
Bus	(7, 8, 8, 9)	(6, 7, 7, 8)	(6, 7, 7, 8)	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry

Wheelbarrow	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)	(1/8, 1/9, 1/9, 1/9)
Animal drawn cart	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(1/8, 1/9, 1/9, 1/9)
Tractor	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)
Mini lorry	(6, 7, 7, 8)	(6, 7, 7, 8)	(5, 6, 6, 7)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)
Lorry	(8, 9, 9, 9)	(8, 9, 9, 9)	(7, 8, 8, 9)	(4, 5, 5, 6)	(1, 1, 1, 2)

Sociologist 2:

Sensitivity	Investment	Stores	Claims
Investment	(1, 1, 1, 2)	(7, 8, 8, 9)	(8, 9, 9, 9)
Stores	(1/7, 1/8, 1/8, 1/9)	(1, 1, 1, 2)	(5, 6, 6, 7)
Claims	(1/8, 1/9, 1/9, 1/9)	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset

Human asset	(1, 1, 1, 2)	(4, 5, 5, 6)	(2, 3, 3, 4)
Productive asset	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(1, 1/2, 1/2, 1/3)
Collective asset	(1/2, 1/3, 1/3, 1/4)	(1, 2, 2, 3)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female headed household
Total population	(1, 1, 1, 2)	(8, 9, 9, 9)	(5, 6, 6, 7)	(6, 7, 7, 8)	(2, 3, 3, 4)	(7, 8, 8, 9)
Women	(1/8, 1/9, 1/9, 1/9)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1, 1/2, 1/2, 1/3)
Elderly	(1/5, 1/6, 1/6, 1/7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(2, 3, 3, 4)	(1/4, 1/5, 1/5, 1/6)	(2, 3, 3, 4)
Children	(1/6, 1/7, 1/7, 1/8)	(3, 4, 4, 5)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(2, 3, 3, 4)
Disabled	(1/2, 1/3, 1/3, 1/4)	(5, 6, 6, 7)	(4, 5, 5, 6)	(3, 4, 4, 5)	(1, 1, 1, 2)	(5, 6, 6, 7)
Female headed household	(1/7, 1/8, 1/8, 1/9)	(1, 2, 2, 3)	(1/2, 1/3, 1/3, 1/4)	(1/2, 1/3, 1/3, 1/4)	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)
Cultivated land	(4, 5, 5, 6)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(4, 5, 5, 6)	(3, 4, 4, 5)
Access to rural road	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)
Rural transport service	(1/3, 1/4, 1/4, 1/5)	(2, 3, 3, 4)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service
Transporting passenger service	(1, 1, 1, 2)	(1/7, 1/8, 1/8, 1/9)
Transporting cargo service	(7, 8, 8, 9)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/8, 1/9, 1/9, 1/9)	(1/6, 1/7, 1/7, 1/8)
Motorcycle	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/7, 1/8, 1/8, 1/9)	(1/6, 1/7, 1/7, 1/8)
Motorised tricycle	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/6, 1/7, 1/7, 1/8)	(1/5, 1/6, 1/6, 1/7)
Private car	(8, 9, 9, 9)	(7, 8, 8, 9)	(6, 7, 7, 8)	(1, 1, 1, 2)	(2, 3, 3, 4)
Bus	(6, 7, 7, 8)	(6, 7, 7, 8)	(5, 6, 6, 7)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry
Wheelbarrow	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)	(1/8, 1/9, 1/9, 1/9)
Animal drawn cart	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)	(1/8, 1/9, 1/9, 1/9)

Tractor	(5, 6, 6, 7)	(6, 7, 7, 8)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)
Mini lorry	(6, 7, 7, 8)	(7, 8, 8, 9)	(5, 6, 6, 7)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Lorry	(8, 9, 9, 9)	(8, 9, 9, 9)	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)

<u>Sociologist 3:</u>

Sensitivity	Investment	Stores	Claims
Investment	(1, 1, 1, 2)	(6, 7, 7, 8)	(8, 9, 9, 9)
Stores	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(4, 5, 5, 6)
Claims	(1/8, 1/9, 1/9, 1/9)	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset
Human asset	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(1/4, 1/5, 1/5, 1/6)

Productive asset	(2, 3, 3, 4)	(1, 1, 1, 2)	(1, 1/2, 1/2, 1/3)
Collective asset	(4, 5, 5, 6)	(1, 2, 2, 3)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female headed household
Total population	(1, 1, 1, 2)	(6, 7, 7, 8)	(3, 4, 4, 5)	(5, 6, 6, 7)	(1, 2, 2, 3)	(7, 8, 8, 9)
Women	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1, 1/2, 1/2, 1/3)
Elderly	(1/3, 1/4, 1/4, 1/5)	(4, 5, 5, 6)	(1, 1, 1, 2)	(3, 4, 4, 5)	(1/4, 1/5, 1/5, 1/6)	(5, 6, 6, 7)
Children	(1/5, 1/6, 1/6, 1/7)	(3, 4, 4, 5)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(3, 4, 4, 5)
Disabled	(1, 1/2, 1/2, 1/3)	(5, 6, 6, 7)	(4, 5, 5, 6)	(3, 4, 4, 5)	(1, 1, 1, 2)	(5, 6, 6, 7)
Female headed household	(1/7, 1/8, 1/8, 1/9)	(1, 2, 2, 3)	(1/5, 1/6, 1/6, 1/7)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Cultivated land	(3, 4, 4, 5)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(5, 6, 6, 7)	(3, 4, 4, 5)
Access to rural road	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)
Rural transport service	(1/3, 1/4, 1/4, 1/5)	(2, 3, 3, 4)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service
Transporting passenger service	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)
Transporting cargo service	(5, 6, 6, 7)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)	(1/6, 1/7, 1/7, 1/8)
Motorcycle	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)
Motorised tricycle	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/6, 1/7, 1/7, 1/8)	(1/5, 1/6, 1/6, 1/7)
Private car	(7, 8, 8, 9)	(5, 6, 6, 7)	(6, 7, 7, 8)	(1, 1, 1, 2)	(3, 4, 4, 5)
Bus	(6, 7, 7, 8)	(6, 7, 7, 8)	(5, 6, 6, 7)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry
Wheelbarrow	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)	(1/8, 1/9, 1/9, 1/9)

Animal drawn cart	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)
Tractor	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)
Mini lorry	(7, 8, 8, 9)	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Lorry	(8, 9, 9, 9)	(6, 7, 7, 8)	(5, 6, 6, 7)	(3, 4, 4, 5)	(1, 1, 1, 2)

Sociologist 4:

Sensitivity	Investment	Stores	Claims
Investment	(1, 1, 1, 2)	(7,8,8,9)	(5,6,6,7)
Stores	(1/7, 1/8, 1/8, 1/9)	(1, 1, 1, 2)	(3,4,4,5)
Claims	(1/5, 1/6, 1/6, 1/7)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset
Human asset	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/2, 1/3, 1/3, 1/4)

Productive asset	(3, 4, 4, 5)	(1, 1, 1, 2)	(1, 1/2, 1/2, 1/3)
Collective asset	(2, 3, 3, 4)	(1, 2, 2, 3)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female headed
Total population	(1, 1, 1, 2)	(7, 8, 8, 9)	(3, 4, 4, 5)	(6, 7, 7, 8)	(1, 2, 2, 3)	(5, 6, 6, 7)
Women	(1/7, 1/8, 1/8, 1/9)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1, 1/2, 1/2, 1/3)	(1/6, 1/7, 1/7, 1/8)	(2, 3, 3, 4)
Elderly	(1, 1/2, 1/2, 1/3)	(4, 5, 5, 6)	(1, 1, 1, 2)	(3, 4, 4, 5)	(1/2, 1/3, 1/3, 1/4)	(2, 3, 3, 4)
Children	(1/6, 1/7, 1/7, 1/8)	(1, 2, 2, 3)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1, 1/2, 1/2,
Disabled	(1/3, 1/4, 1/4, 1/5)	(6, 7, 7, 8)	(2, 3, 3, 4)	(5, 6, 6, 7)	(1, 1, 1, 2)	(4, 5, 5, 6)
Female headed household	(1/5, 1/6, 1/6, 1/7)	(2, 3, 3, 4)	(1/2, 1/3, 1/3, 1/4)	(1, 2, 2, 3)	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)
Cultivated land	(2, 3, 3, 4)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(7, 8, 8, 9)	(4, 5, 5, 6)
Access to rural road	(1/7, 1/8, 1/8, 1/9)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Rural transport service	(1/4, 1/5, 1/5, 1/6)	(3, 4, 4, 5)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service
Transporting passenger service	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)
Transporting cargo service	(4, 5, 5, 6)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)	(1/6, 1/7, 1/7, 1/8)
Motorcycle	(2, 3, 3, 4)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/6, 1/7, 1/7, 1/8)	(1/5, 1/6, 1/6, 1/7)

Motorised tricycle	(5, 6, 6, 7)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/4, 1/5, 1/5, 1/6)
Private car	(7, 8, 8, 9)	(6, 7, 7, 8)	(5, 6, 6, 7)	(1, 1, 1, 2)	(3, 4, 4, 5)
Bus	(6, 7, 7, 8)	(5, 6, 6, 7)	(4, 5, 5, 6)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry
Wheelbarrow	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)	(1/8, 1/9, 1/9, 1/9)
Animal drawn cart	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)
Tractor	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)
Mini lorry	(7, 8, 8, 9)	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Lorry	(8, 9, 9, 9)	(7, 8, 8, 9)	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)

Sociologist 5:

Sensitivity	Investment	Stores	Claims

Investment	(1, 1, 1, 2)	(6, 7, 7, 8)	(8, 9, 9, 9)
Stores	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(4, 5, 5, 6)
Claims	(1/8, 1/9, 1/9, 1/9)	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset
Human asset	(1, 1, 1, 2)	(4, 5, 5, 6)	(5, 6, 6, 7)
Productive asset	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)
Collective asset	(1/5, 1/6, 1/6, 1/7)	(2, 3, 3, 4)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female
Total population	(1, 1, 1, 2)	(6, 7, 7, 8)	(3, 4, 4, 5)	(5, 6, 6, 7)	(4, 5, 5, 6)	(7, 8, 8, 9)
Women	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/4, 1/5, 1/5, 1/6)	(1, 1/2, 1/2,
Elderly	(1/3, 1/4, 1/4, 1/5)	(3, 4, 4, 5)	(1, 1, 1, 2)	(3, 4, 4, 5)	(1/3, 1/4, 1/4, 1/5)	(4, 5, 5, 6)

Children	(1/5, 1/6, 1/6, 1/7)	(5, 6, 6, 7)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(2, 3, 3, 4)
Disabled	(1/4, 1/5, 1/5, 1/6)	(4, 5, 5, 6)	(3, 4, 4, 5)	(4, 5, 5, 6)	(1, 1, 1, 2)	(3, 4, 4, 5)
Female headed household	(1/7, 1/8, 1/8, 1/9)	(1, 2, 2, 3)	(1/4, 1/5, 1/5, 1/6)	(1/2, 1/3, 1/3, 1/4)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(2, 3, 3, 4)
Cultivated land	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(7, 8, 8, 9)	(5, 6, 6, 7)
Access to rural road	(1/7, 1/8, 1/8, 1/9)	(1, 1, 1, 2)	(3, 4, 4, 5)
Rural transport service	(1/5, 1/6, 1/6, 1/7)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service
Transporting passenger service	(1, 1, 1, 2)	(1/7, 1/8, 1/8, 1/9)
Transporting cargo service	(7, 8, 8, 9)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/6, 1/7, 1/7, 1/8)	(1/8, 1/9, 1/9, 1/9)	(1/7, 1/8, 1/8, 1/9)
Motorcycle	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/7, 1/8, 1/8, 1/9)	(1/6, 1/7, 1/7, 1/8)
Motorised tricycle	(6, 7, 7, 8)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/4, 1/5, 1/5, 1/6)
Private car	(8, 9, 9, 9)	(7, 8, 8, 9)	(5, 6, 6, 7)	(1, 1, 1, 2)	(4, 5, 5, 6)
Bus	(7, 8, 8, 9)	(6, 7, 7, 8)	(4, 5, 5, 6)	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry
Wheelbarrow	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)	(1/8, 1/9, 1/9, 1/9)
Animal drawn cart	(5, 6, 6, 7)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)
Tractor	(6, 7, 7, 8)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)
Mini lorry	(7, 8, 8, 9)	(5, 6, 6, 7)	(5, 6, 6, 7)	(1, 1, 1, 2)	(1/6, 1/7, 1/7, 1/8)
Lorry	(8, 9, 9, 9)	(7, 8, 8, 9)	(7, 8, 8, 9)	(6, 7, 7, 8)	(1, 1, 1, 2)

Sociologist 6:

Sensitivity	Investment	Stores	Claims
Investment	(1, 1, 1, 2)	(4, 5, 5, 6)	(6, 7, 7, 8)
Stores	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(3, 4, 4, 5)
Claims	(1/6, 1/7, 1/7, 1/8)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset
Human asset	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)
Productive asset	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Collective asset	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female headed
Total population	(1, 1, 1, 2)	(6, 7, 7, 8)	(3, 4, 4, 5)	(4, 5, 5, 6)	(2, 3, 3, 4)	(7, 8, 8, 9)
Women	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/2, 1/3, 1/3, 1/4)
Elderly	(1/3, 1/4, 1/4, 1/5)	(4, 5, 5, 6)	(1, 1, 1, 2)	(3, 4, 4, 5)	(2, 3, 3, 4)	(5, 6, 6, 7)
Children	(1/4, 1/5, 1/5, 1/6)	(3, 4, 4, 5)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(3, 4, 4, 5)
Disabled	(1/2, 1/3, 1/3, 1/4)	(5, 6, 6, 7)	(1/2, 1/3, 1/3, 1/4)	(3, 4, 4, 5)	(1, 1, 1, 2)	(5, 6, 6, 7)
Female headed household	(1/7, 1/8, 1/8, 1/9)	(2, 3, 3, 4)	(1/5, 1/6, 1/6, 1/7)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(4, 5, 5, 6)
Cultivated land	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(5, 6, 6, 7)	(4, 5, 5, 6)
Access to rural road	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)	(1, 1/2, 1/2, 1/3)
Rural transport service	(1/4, 1/5, 1/5, 1/6)	(1, 2, 2, 3)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service
Transporting passenger service	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)
Transporting cargo service	(4, 5, 5, 6)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/8, 1/9, 1/9, 1/9)	(1/7, 1/8, 1/8, 1/9)
Motorcycle	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/7, 1/8, 1/8, 1/9)	(1/6, 1/7, 1/7, 1/8)
Motorised tricycle	(5, 6, 6, 7)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/6, 1/7, 1/7, 1/8)	(5, 6, 6, 7)
Private car	(8, 9, 9, 9)	(7, 8, 8, 9)	(6, 7, 7, 8)	(1, 1, 1, 2)	(3, 4, 4, 5)
Bus	(7, 8, 8, 9)	(6, 7, 7, 8)	(5, 6, 6, 7)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry
Wheelbarrow	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)	(1/8, 1/9, 1/9, 1/9)
Animal drawn cart	(2, 3, 3, 4)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)

Tractor	(5, 6, 6, 7)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)
Mini lorry	(6, 7, 7, 8)	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Lorry	(8, 9, 9, 9)	(7, 8, 8, 9)	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)

Sociologist 7:

Sensitivity	Investment	Stores	Claims
Investment	(1, 1, 1, 2)	(3, 4, 4, 5)	(7, 8, 8, 9)
Stores	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)	(3, 4, 4, 5)
Claims	(1/7, 1/8, 1/8, 1/9)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset
Human asset	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)
Productive asset	(6, 7, 7, 8)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)

Collective asset	(4, 5, 5, 6)	(3, 4, 4, 5)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female headed
Total population	(1, 1, 1, 2)	(8, 9, 9, 9)	(6, 7, 7, 8)	(4, 5, 5, 6)	(5, 6, 6, 7)	(7, 8, 8, 9)
Women	(1/8, 1/9, 1/9, 1/9)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(1/4, 1/5, 1/5, 1/6)	(1/3, 1/4, 1/4, 1/5)	(1, 1/2, 1/2, 1/3)
Elderly	(1/6, 1/7, 1/7, 1/8)	(2, 3, 3, 4)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(1, 1/2, 1/2, 1/3)	(2, 3, 3, 4)
Children	(1/4, 1/5, 1/5, 1/6)	(4, 5, 5, 6)	(2, 3, 3, 4)	(1, 1, 1, 2)	(1, 2, 2, 3)	(3, 4, 4, 5)
Disabled	(1/5, 1/6, 1/6, 1/7)	(3, 4, 4, 5)	(1, 2, 2, 3)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)	(2, 3, 3, 4)
Female headed household	(1/7, 1/8, 1/8, 1/9)	(1, 2, 2, 3)	(1/2, 1/3, 1/3, 1/4)	(1/3, 1/4, 1/4, 1/5)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(1/7, 1/8, 1/8, 1/9)
Cultivated land	(7, 8, 8, 9)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(6, 7, 7, 8)	(7, 8, 8, 9)
Access to rural road	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(3, 4, 4, 5)
Rural transport service	(1/7, 1/8, 1/8, 1/9)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service
Transporting passenger service	(1, 1, 1, 2)	(1/7, 1/8, 1/8, 1/9)
Transporting cargo service	(7, 8, 8, 9)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(1/4, 1/5, 1/5, 1/6)	(1/7, 1/8, 1/8, 1/9)	(1/6, 1/7, 1/7, 1/8)
Motorcycle	(2, 3, 3, 4)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(1/5, 1/6, 1/6, 1/7)

Motorised tricycle	(4, 5, 5, 6)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/2, 1/3, 1/3, 1/4)
Private car	(7, 8, 8, 9)	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)	(2, 3, 3, 4)
Bus	(6, 7, 7, 8)	(5, 6, 6, 7)	(2, 3, 3, 4)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry
Wheelbarrow	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)	(1/8, 1/9, 1/9, 1/9)
Animal drawn cart	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/6, 1/7, 1/7, 1/8)	(1/8, 1/9, 1/9, 1/9)
Tractor	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/7, 1/8, 1/8, 1/9)
Mini lorry	(7, 8, 8, 9)	(6, 7, 7, 8)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)
Lorry	(8, 9, 9, 9)	(8, 9, 9, 9)	(7, 8, 8, 9)	(4, 5, 5, 6)	(1, 1, 1, 2)

Sociologist 8:

Sensitivity	Investment	Stores	Claims
Investment	(1, 1, 1, 2)	(4, 5, 5, 6)	(6, 7, 7, 8)
Stores	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(3, 4, 4, 5)
Claims	(1/6, 1/7, 1/7, 1/8)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset
Human asset	(1, 1, 1, 2)	(1/6, 1/7, 1/7, 1/8)	(1/3, 1/4, 1/4, 1/5)
Productive asset	(6, 7, 7, 8)	(1, 1, 1, 2)	(2, 3, 3, 4)
Collective asset	(3, 4, 4, 5)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female
Total population	(1, 1, 1, 2)	(7, 8, 8, 9)	(4, 5, 5, 6)	(5, 6, 6, 7)	(2, 3, 3, 4)	(8, 9, 9, 9)
Women	(1/7, 1/8, 1/8, 1/9)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/2, 1/3, 1/3, 1/4)	(1/5, 1/6, 1/6, 1/7)	(1, 2, 2, 3)

Elderly	(1/4, 1/5, 1/5, 1/6)	(3, 4, 4, 5)	(1, 1, 1, 2)	(2, 3, 3, 4)	(1/2, 1/3, 1/3, 1/4)	(4, 5, 5, 6)
Children	(1/5, 1/6, 1/6, 1/7)	(2, 3, 3, 4)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(4, 5, 5, 6)
Disabled	(1/2, 1/3, 1/3, 1/4)	(5, 6, 6, 7)	(2, 3, 3, 4)	(3, 4, 4, 5)	(1, 1, 1, 2)	(6, 7, 7, 8)
Female headed household	(1/8, 1/9, 1/9, 1/9)	(1, 1/2,	(1/4, 1/5, 1/5, 1/6)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)
Cultivated land	(2, 3, 3, 4)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(5, 6, 6, 7)	(6, 7, 7, 8)
Access to rural road	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)	(3, 4, 4, 5)

Rural transport service	(1/6, 1/7, 1/7, 1/8)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service
Transporting passenger service	(1, 1, 1, 2)	(1/7, 1/8, 1/8, 1/9)
Transporting cargo service	(7, 8, 8, 9)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1, 1/2, 1/2, 1/3)	(1/3, 1/4, 1/4, 1/5)	(1/6, 1/7, 1/7, 1/8)	(1/4, 1/5, 1/5, 1/6)
Motorcycle	(1, 2, 2, 3)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(1/5, 1/6, 1/6, 1/7)	(1/3, 1/4, 1/4, 1/5)
Motorised tricycle	(3, 4, 4, 5)	(2, 3, 3, 4)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/3, 1/4, 1/4, 1/5)
Private car	(6, 7, 7, 8)	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(2, 3, 3, 4)

Bus	(4, 5, 5, 6)	(3, 4, 4, 5)	(3, 4, 4, 5)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry
Wheelbarrow	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)	(1/8, 1/9, 1/9, 1/9)
Animal drawn cart	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)
Tractor	(5, 6, 6, 7)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)
Mini lorry	(7, 8, 8, 9)	(6, 7, 7, 8)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Lorry	(8, 9, 9, 9)	(7, 8, 8, 9)	(5, 6, 6, 7)	(3, 4, 4, 5)	(1, 1, 1, 2)

Sociologist 9:

Sensitivity	Investment	Stores	Claims

Investment	(1, 1, 1, 2)	(5, 6, 6, 7)	(7, 8, 8, 9)
Stores	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)	(4, 5, 5, 6)
Claims	(1/7, 1/8, 1/8, 1/9)	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset
Human asset	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(4, 5, 5, 6)
Productive asset	(5, 6, 6, 7)	(1, 1, 1, 2)	(3, 4, 4, 5)
Collective asset	(1/4, 1/5, 1/5, 1/6)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female headed household
Total population	(1, 1, 1, 2)	(6, 7, 7, 8)	(5, 6, 6, 7)	(2, 3, 3, 4)	(1, 2, 2, 3)	(8, 9, 9, 9)

Women	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(1, 1/2, 1/2, 1/3)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(2, 3, 3, 4)
Elderly	(1/5, 1/6, 1/6, 1/7)	(1, 2, 2, 3)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/4, 1/5, 1/5, 1/6)	(3, 4, 4, 5)
Children	(1/2, 1/3, 1/3, 1/4)	(4, 5, 5, 6)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1, 1/2, 1/2, 1/3)	(6, 7, 7, 8)
Disabled	(1, 1/2, 1/2, 1/3)	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 2, 2, 3)	(1, 1, 1, 2)	(7, 8, 8, 9)
Female headed household	(1/8, 1/9, 1/9, 1/9)	(1/2, 1/3, 1/3, 1/4)	(1/3, 1/4, 1/4, 1/5)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(1, 2, 2, 3)
Cultivated land	(1, 1/2, 1/2, 1/3)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(6, 7, 7, 8)	(4, 5, 5, 6)

Access to rural road	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Rural transport service	(1/4, 1/5, 1/5, 1/6)	(3, 4, 4, 5)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service
Transporting passenger service	(1, 1, 1, 2)	(1/7, 1/8, 1/8, 1/9)
Transporting cargo service	(7, 8, 8, 9)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)	(1/6, 1/7, 1/7, 1/8)
Motorcycle	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/4, 1/5, 1/5, 1/6)

Motorised tricycle	(5, 6, 6, 7)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/3, 1/4, 1/4, 1/5)
Private car	(7, 8, 8, 9)	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(3, 4, 4, 5)
Bus	(6, 7, 7, 8)	(4, 5, 5, 6)	(3, 4, 4, 5)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry
Wheelbarrow	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)	(1/8, 1/9, 1/9, 1/9)
Animal drawn cart	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)
Tractor	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)
Mini lorry	(7, 8, 8, 9)	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)
Lorry	(8, 9, 9, 9)	(7, 8, 8, 9)	(6, 7, 7, 8)	(4, 5, 5, 6)	(1, 1, 1, 2)

Sociologist 10:

Sensitivity	Investment	Stores	Claims
Investment	(1, 1, 1, 2)	(8, 9, 9, 9)	(6, 7, 7, 8)
Stores	(1/8, 1/9, 1/9, 1/9)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)
Claims	(1/6, 1/7, 1/7, 1/8)	(4, 5, 5, 6)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset
Human asset	(1, 1, 1, 2)	(3, 4, 4, 5)	(1/6, 1/7, 1/7, 1/8)
Productive asset	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)
Collective asset	(6, 7, 7, 8)	(5, 6, 6, 7)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female headed

Total population	(1, 1, 1, 2)	(8, 9, 9, 9)	(5, 6, 6, 7)	(2, 3, 3, 4)	(1, 2, 2, 3)	(7, 8, 8, 9)
Women	(1/8, 1/9, 1/9, 1/9)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)	(1, 1/2, 1/2, 1/3)
Elderly	(1/5, 1/6, 1/6, 1/7)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/4, 1/5, 1/5, 1/6)	(2, 3, 3, 4)
Children	(1/2, 1/3, 1/3, 1/4)	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1, 1/2, 1/2, 1/3)	(5, 6, 6, 7)
Disabled	(1, 1/2, 1/2, 1/3)	(7, 8, 8, 9)	(4, 5, 5, 6)	(1, 2, 2, 3)	(1, 1, 1, 2)	(6, 7, 7, 8)
Female headed household	(1/7, 1/8, 1/8, 1/9)	(1, 2, 2, 3)	(1/2, 1/3, 1/3, 1/4)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(4, 5, 5, 6)
Cultivated land	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(4, 5, 5, 6)	(5, 6, 6, 7)
Access to rural road	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(3, 4, 4, 5)

Rural transport service	(1/5, 1/6, 1/6, 1/7)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service
Transporting passenger service	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Transporting cargo service	(3, 4, 4, 5)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/8, 1/9, 1/9, 1/9)	(1/6, 1/7, 1/7, 1/8)
Motorcycle	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/7, 1/8, 1/8, 1/9)	(1/5, 1/6, 1/6, 1/7)
Motorised tricycle	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/6, 1/7, 1/7, 1/8)	(1/4, 1/5, 1/5, 1/6)
Private car	(8, 9, 9, 9)	(7, 8, 8, 9)	(6, 7, 7, 8)	(1, 1, 1, 2)	(3, 4, 4, 5)

Bus	(6, 7, 7, 8)	(5, 6, 6, 7)	(4, 5, 5, 6)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry
Wheelbarrow	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)	(1/8, 1/9, 1/9, 1/9)
Animal drawn cart	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)
Tractor	(6, 7, 7, 8)	(5, 6, 6, 7)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)
Mini lorry	(7, 8, 8, 9)	(6, 7, 7, 8)	(5, 6, 6, 7)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Lorry	(8, 9, 9, 9)	(7, 8, 8, 9)	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)

Sociologist 11:

Sensitivity	Investment	Stores	Claims

Investment	(1, 1, 1, 2)	(6, 7, 7, 8)	(5, 6, 6, 7)
Stores	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Claims	(1/5, 1/6, 1/6, 1/7)	(3, 4, 4, 5)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset
Human asset	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(3, 4, 4, 5)
Productive asset	(5, 6, 6, 7)	(1, 1, 1, 2)	(2, 3, 3, 4)
Collective asset	(1/3, 1/4, 1/4, 1/5)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female headed household
Total population	(1, 1, 1, 2)	(6, 7, 7, 8)	(2, 3, 3, 4)	(3, 4, 4, 5)	(1, 2, 2, 3)	(7, 8, 8, 9)

Women	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1, 2, 2, 3)
Elderly	(1/2, 1/3, 1/3, 1/4)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1, 2, 2, 3)	(1,1/2, 1/2, 1/3)	(5, 6, 6, 7)
Children	(1/3, 1/4, 1/4, 1/5)	(3, 4, 4, 5)	(1, 1/2, 1/2, 1/3)	(1, 1, 1, 2)	(1,1/2, 1/2, 1/3)	(4, 5, 5, 6)
Disabled	(1, 1/2, 1/2, 1/3)	(5, 6, 6, 7)	(1, 2, 2, 3)	(1, 2, 2, 3)	(1, 1, 1, 2)	(6, 7, 7, 8)
Female headed household	(1/7, 1/8, 1/8, 1/9)	(1, 1/2, 1/2, 1/3)	(1/5, 1/6, 1/6, 1/7)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(3, 4, 4, 5)
Cultivated land	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(1/6, 1/7, 1/7, 1/8)	(1/4, 1/5, 1/5, 1/6)

Access to rural road	(6, 7, 7, 8)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Rural transport service	(4, 5, 5, 6)	(3, 4, 4, 5)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service
Transporting passenger service	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)
Transporting cargo service	(5, 6, 6, 7)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1/8, 1/9, 1/9, 1/9)	(1/7, 1/8, 1/8, 1/9)
Motorcycle	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/7, 1/8, 1/8, 1/9)	(1/6, 1/7, 1/7, 1/8)
Motorised tricycle	(5, 6, 6, 7)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)

Private car	(8, 9, 9, 9)	(7, 8, 8, 9)	(4, 5, 5, 6)	(1, 1, 1, 2)	(3, 4, 4, 5)
Bus	(7, 8, 8, 9)	(6, 7, 7, 8)	(5, 6, 6, 7)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry
Wheelbarrow	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)	(1/8, 1/9, 1/9, 1/9)
Animal drawn cart	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/4, 1/5, 1/5, 1/6)	(1/7, 1/8, 1/8, 1/9)
Tractor	(5, 6, 6, 7)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/4, 1/5, 1/5, 1/6)
Mini lorry	(6, 7, 7, 8)	(4, 5, 5, 6)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Lorry	(8, 9, 9, 9)	(7, 8, 8, 9)	(4, 5, 5, 6)	(3, 4, 4, 5)	(1, 1, 1, 2)

Sociologist 12

Sensitivity	Investment	Stores	Claims
Investment	(1, 1, 1, 2)	(6, 7, 7, 8)	(4, 5, 5, 6)
Stores	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Claims	(1/4, 1/5, 1/5, 1/6)	(3, 4, 4, 5)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset
Human asset	(1, 1, 1, 2)	(4, 5, 5, 6)	(3, 4, 4, 5)
Productive asset	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(2, 3, 3, 4)
Collective asset	(1/3, 1/4, 1/4, 1/5)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female headed household
Total population	(1, 1, 1, 2)	(6, 7, 7, 8)	(5, 6, 6, 7)	(3, 4, 4, 5)	(2, 3, 3, 4)	(7, 8, 8, 9)
Women	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(1, 1/2, 1/2, 1/3)	(1/3, 1/4, 1/4, 1/5)	(1/4, 1/5, 1/5, 1/6)	(1, 2, 2, 3)

Elderly	(1/5, 1/6, 1/6, 1/7)	(1, 2, 2, 3)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(1/3, 1/4, 1/4, 1/5)	(2, 3, 3, 4)
Children	(1/3, 1/4, 1/4, 1/5)	(3, 4, 4, 5)	(2, 3, 3, 4)	(1, 1, 1, 2)	(1, 1/2, 1/2, 1/3)	(4, 5, 5, 6)
Disabled	(1/2, 1/3, 1/3, 1/4)	(4, 5, 5, 6)	(3, 4, 4, 5)	(1, 2, 2, 3)	(1, 1, 1, 2)	(5, 6, 6, 7)
Female headed household	(1/7, 1/8, 1/8, 1/9)	(1, 1/2, 1/2, 1/3)	(1/2, 1/3, 1/3, 1/4)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(1, 2, 2, 3)
Cultivated land	(1,1/ 2,1/ 2, 1/3)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(4, 5, 5, 6)	(6, 7, 7, 8)
Access to rural road	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Rural transport service	(1/6, 1/7, 1/7, 1/8)	(3, 4, 4, 5)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service
Transporting passenger service	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Transporting cargo service	(3, 4, 4, 5)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/8, 1/9, 1/9, 1/9)	(1/7, 1/8, 1/8, 1/9)
Motorcycle	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/7, 1/8, 1/8, 1/9)	(1/6, 1/7, 1/7, 1/8)
Motorised tricycle	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/6, 1/7, 1/7, 1/8)	(1/5, 1/6, 1/6, 1/7)
Private car	(8, 9, 9, 9)	(7, 8, 8, 9)	(6, 7, 7, 8)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)
Bus	(7, 8, 8, 9)	(6, 7, 7, 8)	(5, 6, 6, 7)	(2, 3, 3, 4)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry
Wheelbarrow	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)	(1/8, 1/9, 1/9, 1/9)
Animal drawn cart	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)
Tractor	(5, 6, 6, 7)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)
Mini lorry	(6, 7, 7, 8)	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)
Lorry	(8, 9, 9, 9)	(7, 8, 8, 9)	(6, 7, 7, 8)	(4, 5, 5, 6)	(1, 1, 1, 2)

Sociologist 13:

Sensitivity	Investment	Stores	Claims
Investment	(1, 1, 1, 2)	(6, 7, 7, 8)	(4, 5, 5, 6)
Stores	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Claims	(1/4, 1/5, 1/5, 1/6)	(3, 4, 4, 5)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset
Human asset	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/3, 1/4, 1/4, 1/5)
Productive asset	(4, 5, 5, 6)	(1, 1, 1, 2)	(2, 3, 3, 4)
Collective asset	(3, 4, 4, 5)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female headed
Total population	(1, 1, 1, 2)	(8, 9, 9, 9)	(4, 5, 5, 6)	(5, 6, 6, 7)	(1, 2, 2, 3)	(7, 8, 8, 9)
Women	(1/8, 1/9, 1/9, 1/9)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/3, 1/4, 1/4, 1/5)	(1/7, 1/8, 1/8, 1/9)	(1, 1/2, 1/2, 1/3)
Elderly	(1/4, 1/5, 1/5, 1/6)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1, 2, 2, 3)	(1/3, 1/4, 1/4, 1/5)	(3, 4, 4, 5)
Children	(1/5, 1/6, 1/6, 1/7)	(3, 4, 4, 5)	(1, 1/2, 1/2, 1/3)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(2, 3, 3, 4)
Disabled	(1, 1/2, 1/2, 1/3)	(7, 8, 8, 9)	(3, 4, 4, 5)	(4, 5, 5, 6)	(1, 1, 1, 2)	(6, 7, 7, 8)
Female headed household	(1/7, 1/8, 1/8, 1/9)	(1, 2, 2, 3)	(1/3, 1/4, 1/4, 1/5)	(1/2, 1/3, 1/3, 1/4)	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(3, 4, 4, 5)
Cultivated land	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(5, 6, 6, 7)	(7, 8, 8, 9)
Access to rural road	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)	(3, 4, 4, 5)
Rural transport service	(1/7, 1/8, 1/8, 1/9)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service
Transporting passenger service	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Transporting cargo service	(3, 4, 4, 5)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)	(1/8, 1/9, 1/9, 1/9)	(1/7, 1/8, 1/8, 1/9)
Motorcycle	(5, 6, 6, 7)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/7, 1/8, 1/8, 1/9)	(1/6, 1/7, 1/7, 1/8)
Motorised tricycle	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/4, 1/5, 1/5, 1/6)
Private car	(8, 9, 9, 9)	(7, 8, 8, 9)	(5, 6, 6, 7)	(1, 1, 1, 2)	(3, 4, 4, 5)
Bus	(7, 8, 8, 9)	(6, 7, 7, 8)	(4, 5, 5, 6)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry
Wheelbarrow	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)	(1/8, 1/9, 1/9, 1/9)
Animal drawn cart	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)

Tractor	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/6, 1/7, 1/7, 1/8)
Mini lorry	(7, 8, 8, 9)	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Lorry	(8, 9, 9, 9)	(7, 8, 8, 9)	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)

Sociologist 14:

Sensitivity	Investment	Stores	Claims
Investment	(1, 1, 1, 2)	(3, 4, 4, 5)	(4, 5, 5, 6)
Stores	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)	(2, 3, 3, 4)
Claims	(1/4, 1/5, 1/5, 1/6)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset

Human asset	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(3, 4, 4, 5)
Productive asset	(5, 6, 6, 7)	(1, 1, 1, 2)	(6, 7, 7, 8)
Collective asset	(1/3, 1/4, 1/4, 1/5)	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female headed household
Total population	(1, 1, 1, 2)	(8, 9, 9, 9)	(3, 4, 4, 5)	(2, 3, 3, 4)	(1, 2, 2, 3)	(7, 8, 8, 9)
Women	(1/8, 1/9, 1/9, 1/9)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)	(1, 1/2, 1/2, 1/3)
Elderly	(1/3, 1/4, 1/4, 1/5)	(5, 6, 6, 7)	(1, 1, 1, 2)	(1, 1/2, 1/2, 1/3)	(1/2, 1/3, 1/3, 1/4)	(4, 5, 5, 6)
Children	(1/2, 1/3, 1/3, 1/4)	(6, 7, 7, 8)	(1, 2, 2, 3)	(1, 1, 1, 2)	(1, 1/2, 1/2, 1/3)	(5, 6, 6, 7)
Disabled	(1, 1/2, 1/2, 1/3)	(7, 8, 8, 9)	(2, 3, 3, 4)	(1, 2, 2, 3)	(1, 1, 1, 2)	(6, 7, 7, 8)

Female headed household	(1/7, 1/8, 1/8, 1/9)	(1, 2, 2, 3)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)
Cultivated land	(4, 5, 5, 6)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(3, 4, 4, 5)	(2, 3, 3, 4)
Access to rural road	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)	(1, 1/2, 1/2, 1/3)
Rural transport service	(1/2, 1/3, 1/3, 1/4)	(1, 2, 2, 3)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service

Transporting passenger service	(1, 1, 1, 2)	(1/6, 1/7, 1/7, 1/8)
Transporting cargo service	(6, 7, 7, 8)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/8, 1/9, 1/9, 1/9)	(1/7, 1/8, 1/8, 1/9)
Motorcycle	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/6, 1/7, 1/7, 1/8)	(1/5, 1/6, 1/6, 1/7)
Motorised tricycle	(5, 6, 6, 7)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/3, 1/4, 1/4, 1/5)
Private car	(8, 9, 9, 9)	(6, 7, 7, 8)	(4, 5, 5, 6)	(1, 1, 1, 2)	(3, 4, 4, 5)
Bus	(7, 8, 8, 9)	(5, 6, 6, 7)	(3, 4, 4, 5)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry
Wheelbarrow	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)	(1/8, 1/9, 1/9, 1/9)
Animal drawn cart	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)
Tractor	(6, 7, 7, 8)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)
Mini lorry	(7, 8, 8, 9)	(6, 7, 7, 8)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Lorry	(8, 9, 9, 9)	(7, 8, 8, 9)	(5, 6, 6, 7)	(3, 4, 4, 5)	(1, 1, 1, 2)

Sociologist 15:

Sensitivity	Investment	Stores	Claims
Investment	(1, 1, 1, 2)	(6, 7, 7, 8)	(4, 5, 5, 6)
Stores	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)

Claims	(1/4, 1/5, 1/5, 1/6)	(3, 4, 4, 5)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset
Human asset	(1, 1, 1, 2)	(4, 5, 5, 6)	(5, 6, 6, 7)
Productive asset	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(3, 4, 4, 5)
Collective asset	(1/5, 1/6, 1/6, 1/7)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female
Total population	(1, 1, 1, 2)	(6, 7, 7, 8)	(2, 3, 3, 4)	(3, 4, 4, 5)	(1, 2, 2, 3)	(8, 9, 9, 9)
Women	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(2, 3, 3, 4)
Elderly	(1/2, 1/3, 1/3, 1/4)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1, 2, 2, 3)	(1, 1/2, 1/2, 1/3)	(6, 7, 7, 8)
Children	(1/3, 1/4, 1/4, 1/5)	(3, 4, 4, 5)	(1, 1/2, 1/2, 1/3)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(5, 6, 6, 7)
Disabled	(1, 1/2, 1/2, 1/3)	(5, 6, 6, 7)	(1, 2, 2, 3)	(2, 3, 3, 4)	(1, 1, 1, 2)	(7, 8, 8, 9)

Female headed household	(1/8, 1/9, 1/9, 1/9)	(1/2, 1/3, 1/3, 1/4)	(1/6, 1/7, 1/7, 1/8)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)
Cultivated land	(2, 3, 3, 4)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(6, 7, 7, 8)	(5, 6, 6, 7)
Access to rural road	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Rural transport service	(1/5, 1/6, 1/6, 1/7)	(3, 4, 4, 5)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service
Transporting passenger service	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)
Transporting cargo service	(4, 5, 5, 6)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(1/8, 1/9, 1/9, 1/9)	(1/7, 1/8, 1/8, 1/9)
Motorcycle	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/7, 1/8, 1/8, 1/9)	(1/6, 1/7, 1/7, 1/8)
Motorised tricycle	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/6, 1/7, 1/7, 1/8)	(1/5, 1/6, 1/6, 1/7)
Private car	(8, 9, 9, 9)	(7, 8, 8, 9)	(6, 7, 7, 8)	(1, 1, 1, 2)	(3, 4, 4, 5)
Bus	(7, 8, 8, 9)	(6, 7, 7, 8)	(5, 6, 6, 7)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry
Wheelbarrow	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)	(1/8, 1/9, 1/9, 1/9)

Animal drawn cart	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/5, 1/6, 1/6, 1/7)	(1/7, 1/8, 1/8, 1/9)
Tractor	(5, 6, 6, 7)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/5, 1/6, 1/6, 1/7)
Mini lorry	(6, 7, 7, 8)	(5, 6, 6, 7)	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)
Lorry	(8, 9, 9, 9)	(7, 8, 8, 9)	(5, 6, 6, 7)	(2, 3, 3, 4)	(1, 1, 1, 2)

Sociologist 16:

Sensitivity	Investment	Stores	Claims
Investment	(1, 1, 1, 2)	(6, 7, 7, 8)	(4, 5, 5, 6)
Stores	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Claims	(1/4, 1/5, 1/5, 1/6)	(3, 4, 4, 5)	(1, 1, 1, 2)

Investment	Human asset	Productive asset	Collective asset
Human asset	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)

Productive asset	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Collective asset	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)

Human asset	Total population	Women	Elderly	Children	Disabled	Female headed household
Total population	(1, 1, 1, 2)	(8, 9, 9, 9)	(3, 4, 4, 5)	(4, 5, 5, 6)	(2, 3, 3, 4)	(6, 7, 7, 8)
Women	(1/8, 1/9, 1/9, 1/9)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(1/2, 1/3, 1/3, 1/4)
Elderly	(1/3, 1/4, 1/4, 1/5)	(5, 6, 6, 7)	(1, 1, 1, 2)	(1, 2, 2, 3)	(1, 1/2, 1/2, 1/3)	(4, 5, 5, 6)
Children	(1/4, 1/5, 1/5, 1/6)	(4, 5, 5, 6)	(1, 1/2, 1/2, 1/3)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(2, 3, 3, 4)
Disabled	(1/2, 1/3, 1/3, 1/4)	(6, 7, 7, 8)	(1, 2, 2, 3)	(2, 3, 3, 4)	(1, 1, 1, 2)	(4, 5, 5, 6)
Female headed household	(1/6, 1/7, 1/7, 1/8)	(2, 3, 3, 4)	(1/4, 1/5, 1/5, 1/6)	(1/2, 1/3, 1/3, 1/4)	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)

Productive asset	Livestock	Cultivated land
Livestock	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)
Cultivated land	(4, 5, 5, 6)	(1, 1, 1, 2)

Collective asset	Rural road route condition	Access to rural road	Rural transport service
Rural road route condition	(1, 1, 1, 2)	(6, 7, 7, 8)	(7, 8, 8, 9)
Access to rural road	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)	(3, 4, 4, 5)
Rural transport service	(1/7, 1/8, 1/8, 1/9)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Rural transport service	Transporting passenger service	Transporting cargo service
Transporting passenger service	(1, 1, 1, 2)	(1/7, 1/8, 1/8, 1/9)
Transporting cargo service	(7, 8, 8, 9)	(1, 1, 1, 2)

Transporting passenger service	Bicycle	Motorcycle	Motorised tricycle	Private car	Bus
Bicycle	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/4, 1/5, 1/5, 1/6)	(1/8, 1/9, 1/9, 1/9)	(1/7, 1/8, 1/8, 1/9)
Motorcycle	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/7, 1/8, 1/8, 1/9)	(1/6, 1/7, 1/7, 1/8)
Motorised tricycle	(4, 5, 5, 6)	(3, 4, 4, 5)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/4, 1/5, 1/5, 1/6)
Private car	(8, 9, 9, 9)	(7, 8, 8, 9)	(5, 6, 6, 7)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Bus	(7, 8, 8, 9)	(6, 7, 7, 8)	(4, 5, 5, 6)	(3, 4, 4, 5)	(1, 1, 1, 2)

Transporting cargo service	Wheelbarrow	Animal drawn cart	Tractor	Mini lorry	Lorry
Wheelbarrow	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)	(1/8, 1/9, 1/9, 1/9)
Animal drawn cart	(4, 5, 5, 6)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)	(1/7, 1/8, 1/8, 1/9)

Tractor	(6, 7, 7, 8)	(5, 6, 6, 7)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)
Mini lorry	(7, 8, 8, 9)	(6, 7, 7, 8)	(5, 6, 6, 7)	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)
Lorry	(8, 9, 9, 9)	(7, 8, 8, 9)	(6, 7, 7, 8)	(3, 4, 4, 5)	(1, 1, 1, 2)

Resilience:

Road manager 1:

Human resource	Labourer	Supervisor	Technician	Monitoring
Labourer	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(1/3, 1/4, 1/4, 1/5)	(2, 3, 3, 4)
Supervisor	(5, 6, 6, 7)	(1, 1, 1, 2)	(1/2, 1/3, 1/3, 1/4)	(7, 8, 8, 9)
Technician	(3, 4, 4, 5)	(2, 3, 3, 4)	(1, 1, 1, 2)	(5, 6, 6, 7)
Monitoring	(1/2, 1/3, 1/3, 1/4)	(1/7, 1/8, 1/8, 1/9)	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)

Road manager 2:

Human resource	Labourer	Supervisor	Technician	Monitoring
Labourer	(1, 1, 1, 2)	(1/7, 1/8, 1/8, 1/9)	(1/5, 1/6, 1/6, 1/7)	(2, 3, 3, 4)
Supervisor	(7, 8, 8, 9)	(1, 1, 1, 2)	(2, 3, 3, 4)	(8, 9, 9, 9)
Technician	(5, 6, 6, 7)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)	(7, 8, 8, 9)
Monitoring	(1/2, 1/3, 1/3, 1/4)	(1/8, 1/9, 1/9, 1/9)	(1/7, 1/8, 1/8, 1/9)	(1, 1, 1, 2)

Road manager 3:

Human resource	Labourer	Supervisor	Technician	Monitoring
Labourer	(1, 1, 1, 2)	(1/7, 1/8, 1/8, 1/9)	(1/5, 1/6, 1/6, 1/7)	(1/3, 1/4, 1/4, 1/5)
Supervisor	(7, 8, 8, 9)	(1, 1, 1, 2)	(2, 3, 3, 4)	(4, 5, 5, 6)
Technician	(5, 6, 6, 7)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)	(2, 3, 3, 4)
Monitoring	(3, 4, 4, 5)	(1/4, 1/5, 1/5, 1/6)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)

Vulnerability:

Vulnerability	Exposure	Sensitivity	Resilience
Exposure	(1, 1, 1, 2)	(5, 6, 6, 7)	(7, 8, 8, 9)
Sensitivity	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)	(3, 4, 4, 5)
Resilience	(1/7, 1/8, 1/8, 1/9)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Vulnerability	Exposure	Sensitivity	Resilience
Exposure	(1, 1, 1, 2)	(3, 4, 4, 5)	(1/2, 1/3, 1/3, 1/4)
Sensitivity	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)
Resilience	(2, 3, 3, 4)	(5, 6, 6, 7)	(1, 1, 1, 2)

Vulnerability	Exposure	Sensitivity	Resilience

Exposure	(1, 1, 1, 2)	(4, 5, 5, 6)	(7, 8, 8, 9)
Sensitivity	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(4, 5, 5, 6)
Resilience	(1/7, 1/8, 1/8, 1/9)	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)

Vulnerability	Exposure	Sensitivity	Resilience
Exposure	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(3, 4, 4, 5)
Sensitivity	(3, 4, 4, 5)	(1, 1, 1, 2)	(7, 8, 8, 9)
Resilience	(1/3, 1/4, 1/4, 1/5)	(1/7, 1/8, 1/8, 1/9)	(1, 1, 1, 2)

Vulnerability	Exposure	Sensitivity	Resilience
Exposure	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(1/6, 1/7, 1/7, 1/8)

Sensitivity	(3, 4, 4, 5)	(1, 1, 1, 2)	(3, 4, 4, 5)
Resilience	(6, 7, 7, 8)	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)

Vulnerability	Exposure	Sensitivity	Resilience
Exposure	(1, 1, 1, 2)	(1/5, 1/6, 1/6, 1/7)	(3, 4, 4, 5)
Sensitivity	(5, 6, 6, 7)	(1, 1, 1, 2)	(8, 9, 9, 9)
Resilience	(1/3, 1/4, 1/4, 1/5)	(1/8, 1/9, 1/9, 1/9)	(1, 1, 1, 2)

Vulnerability	Exposure	Sensitivity	Resilience
Exposure	(1, 1, 1, 2)	(4, 5, 5, 6)	(5, 6, 6, 7)
Sensitivity	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(2, 3, 3, 4)

Resilience	(1/5, 1/6, 1/6, 1/7)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)

Vulnerability	Exposure	Sensitivity	Resilience
Exposure	(1, 1, 1, 2)	(5, 6, 6, 7)	(7, 8, 8, 9)
Sensitivity	(1/5, 1/6, 1/6, 1/7)	(1, 1, 1, 2)	(2, 3, 3, 4)
Resilience	(1/7, 1/8, 1/8, 1/9)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)

Vulnerability	Exposure	Sensitivity	Resilience
Exposure	(1, 1, 1, 2)	(1/6, 1/7, 1/7, 1/8)	(4, 5, 5, 6)
Sensitivity	(6, 7, 7, 8)	(1, 1, 1, 2)	(8, 9, 9, 9)
Resilience	(1/4, 1/5, 1/5, 1/6)	(1/8, 1/9, 1/9, 1/9)	(1, 1, 1, 2)

Vulnerability	Exposure	Sensitivity	Resilience
Exposure	(1, 1, 1, 2)	(3, 4, 4, 5)	(7, 8, 8, 9)
Sensitivity	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)	(4, 5, 5, 6)
Resilience	(1/7, 1/8, 1/8, 1/9)	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)

Vulnerability	Exposure	Sensitivity	Resilience
Exposure	(1, 1, 1, 2)	(3, 4, 4, 5)	(4, 5, 5, 6)
Sensitivity	(1/3, 1/4, 1/4, 1/5)	(1, 1, 1, 2)	(1, 2, 2, 3)
Resilience	(1/4, 1/5, 1/5, 1/6)	(1, 1/2, 1/2, 1/3)	(1, 1, 1, 2)

Vulnerability	Exposure	Sensitivity	Resilience

Exposure	(1, 1, 1, 2)	(1/4, 1/5, 1/5, 1/6)	(3, 4, 4, 5)
Sensitivity	(4, 5, 5, 6)	(1, 1, 1, 2)	(8, 9, 9, 9)
Resilience	(1/3, 1/4, 1/4, 1/5)	(1/8, 1/9, 1/9, 1/9)	(1, 1, 1, 2)

Vulnerability	Exposure	Sensitivity	Resilience
Exposure	(1, 1, 1, 2)	(4, 5, 5, 6)	(6, 7, 7, 8)
Sensitivity	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)	(2, 3, 3, 4)
Resilience	(1/6, 1/7, 1/7, 1/8)	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)

Vulnerability	Exposure	Sensitivity	Resilience
Exposure	(1, 1, 1, 2)	(1/3, 1/4, 1/4, 1/5)	(4, 5, 5, 6)

Sensitivity	(3, 4, 4, 5)	(1, 1, 1, 2)	(7, 8, 8, 9)
Resilience	(1/4, 1/5, 1/5, 1/6)	(1/7, 1/8, 1/8, 1/9)	(1, 1, 1, 2)

Vulnerability	Exposure	Sensitivity	Resilience
Exposure	(1, 1, 1, 2)	(2, 3, 3, 4)	(5, 6, 6, 7)
Sensitivity	(1/2, 1/3, 1/3, 1/4)	(1, 1, 1, 2)	(4, 5, 5, 6)
Resilience	(1/5, 1/6, 1/6, 1/7)	(1/4, 1/5, 1/5, 1/6)	(1, 1, 1, 2)

Vulnerability	Exposure	Sensitivity	Resilience
Exposure	(1, 1, 1, 2)	(1, 1/2, 1/2, 1/3)	(5, 6, 6, 7)
Sensitivity	(1, 2, 2, 3)	(1, 1, 1, 2)	(6, 7, 7, 8)

Resilience	(1/5, 1/6, 1/6, 1/7)	(1/6, 1/7, 1/7, 1/8)	(1, 1, 1, 2)

Appendix E: Expert opinions on numerical estimation

Exposure:

Questions		Units	Village name											
			Ganyan			Xiniu			Xiawu			Shuiying		
1.1 Road access loss risk			Expert No.			Expert No.			Expert No.			Expert No.		
Risk category	Risk events		1	2	3	1	2	3	1	2	3	1	2	3
Agriculture	The transportation of tobacco leaf	The number of people affected	Between 30 and 55	Between 27 and 65	Between 25 and 40	Between 18 and 30 and most likely to be 23	Between 10 and 20	Between 25 and 35	Between 10 and 25 and most likely to be 15	Between 16 and 24 and most likely to be 19	Between 20 and 40	Between 4 and 8	Between 10 and 12	Between 5 and 15 and most likely to be 10

	The transportation of water/fertilizer for irrigation/fertilization		Between 10 and 20 and most likely to be 15	Between 27 and 32	Between 15 and 28	Between 17 and 26	Between 10 and 30 and most likely to be 20	Between 20 and 30	Between 25 and 38	Between 30 and 40 and most likely to be 35	Between 30 and 35	Between 30 and 40 and most likely to be 35	Between 20 and 50 and most likely between 30 and 40	Between 25 and 35
	The transportation of grass for feeding animals (e.g. pigs)		Between 8 and 16	Between 15 and 25 and most likely to be 20	Between 20 and 40 and most likely to be 30	Between 18 and 30 and most likely to be 23	Between 25 and 40 and most likely to be 33	Between 15 and 25	Between 18 and 25 and most likely between 20 and 22	Between 20 and 25	Between 15 and 35 and most likely to be 25	Between 13 and 28	Between 20 and 30 and most likely to be 25	Between 30 and 50
	The extension worker's visit		Between 30 and 50	Between 40 and 80 and	Between 30 and 50	Between 20 and 40	Between 30 and 70	Between 20 and 50 and most	Between 50 and 100 and most likely	Between 70 and 100	Between 65 and 75	Between 35 and 45 and most	Between 40 and 60	Between 30 and 70

				most likely 60				likely to be 30	between 70 and 80			likely to be 40		
Education	The access to school	The number of people affected	Between 40 and 70 and most likely between 50 and 60	Between 50 and 80	Between 30 and 50 and most likely to be 40	Between 30 and 50	Between 40 and 80 and most likely to be 60	Between 50 and 60	Between 35 and 55	Between 50 and 60	Between 30 and 50	Between 50 and 60	Between 30 and 50	Between 30 and 60
	The health educator's visiting		Between 20 and 40	Between 50 and 80	Between 20 and 60	Between 50 and 70	Between 30 and 50 and most likely to be 40	Between 30 and 80	Between 30 and 50 and most likely to be 40	Between 30 and 60 and most likely between 40 and 50	Between 40 and 60 and most likely to be 50	Between 30 and 40	Between 20 and 50 and most likely to be 35	Between 40 and 50

	Labour training		Between 70 and 100 and most likely between 80 and 90	Between 90 and 110 and most likely to be 100	Between 50 and 100 and most likely to be 75	Between 65 and 90 and most likely to be 75	Between 80 and 120	Between 60 and 80 and most likely to be 70	Between 100 and 200 and most likely between 140 and 170	Between 70 and 150 and most likely to be 120	Between 90 and 120	Between 60 and 70	Between 50 and 80 and most likely between 60 and 70	Between 40 and 70 and most likely between 50 and 60
Employment	Employee attendance	The number of people affected	Between 10 and 30	Between 20 and 35 and most likely to be 30	Between 10 and 40 and most likely to be 25	Between 30 and 40	Between 25 and 55 and most likely between 35 and 45	Between 40 and 50 and most likely to be 45	Between 30 and 40	Between 15 and 35 and most likely to be 25	Between 20 and 30	Between 30 and 50 and most likely to be 40	Between 50 and 60	Between 45 and 65

	The access to perform the traditional marriage		Between 5 and 10	Between 5 and 10	Between 3 and 7 and most likely to be 5	between 3 and 5	Between 2 and 7 and most likely to be 5	Between 2 and 6	Between 15 and 20	Between 10 and 20	Between 7 and 15	Between 3 and 8	Between 5 and 10	Between 5 and 10
	The access to perform the traditional funeral		Between 3 and 7	Between 3 and 7	Between 5 and 10 and most likely to be 8	Between 2 and 5	Between 3 and 5 and most likely to be 4	Between 3 and 6	Between 5 and 9	Between 3 and 7	Between 6 and 11	Between 2 and 3	Between 5 and 8	Between 2 and 5
	The potential opportunities to be employed		Between 40 and 80 and most likely between 50 and 70	Between 60 and 100 and most likely between	Between 50 and 120 and most likely between	Between 45 and 75 and most likely to be 60	Between 50 and 75	Between 40 and 80 and most likely between	Between 65 and 86 and most likely to be 75	Between 40 and 80 and most likely between	Between 50 and 70 and most likely to be 60	Between 50 and 60	Between 30 and 80 and most likely to	Between 50 and 80 and most likely to be 65

				70 and 90	70 and 90			50 and 60		60 and 70			be 50 and 60	
Health	Buying medication	The number of people affected	Between 20 and 30	Between 10 and 40 and most likely to be 27	Between 15 and 30	Between 20 and 50	Between 35 and 45 and most likely to be 40	Between 30 and 50	Between 25 and 35	Between 15 and 20	Between 20 and 30	Between 15 and 20	Between 30 and 40 and most likely to be 35	Between 20 and 40
	Emergency service		Between 10 and 20 and most likely to be 15	Between 15 and 25	Between 5 and 15	Between 5 and 10	Between 7 and 20	Between 3 and 8	Between 5 and 11	Between 7 and 10	Between 15 and 20	Between 3 and 5	Between 5 and 8	Between 3 and 10

	The access to health centres		Between 50 and 80 and most likely between 60 and 70	Between 60 and 80	Between 40 and 70 and most likely to be 55	Between 20 and 30	Between 30 and 50	Between 25 and 40	Between 45 and 65 and most likely to be 55	Between 30 and 70 and most likely between 50 and 60	Between 50 and 60	Between 30 and 50 and most likely to be 40	Between 50 and 60	Between 50 and 60
	The access to maternity centres		Between 15 and 20 and most likely to be 17	Between 10 and 25 and most likely to be 20	Between 20 and 30	Between 10 and 20	Between 15 and 20 and most likely to be 18	Between 20 and 25	Between 12 and 15	Between 10 and 20 and most likely to be 15	Between 20 and 25	Between 5 and 10	Between 15 and 20	Between 10 and 20 and most likely to be 15
	The immunisation programs		Between 30 to 40	Between 20 and 30	Between 10 and 25	Between 20 and 25	Between 10 and 35 and most	Between 15 and 30	Between 30 and 40	Between 25 and 50	Between 20 and 40	Between 15 and 20	Between 10 and 15	Between 10 and 20 and most

							likely to be 20							likely to be 15
Income and consumption	Buying poultry (e.g. chicken)	The number of people affected	Between 15 and 20 and most likely to be 17	Between 10 and 20	Between 20 and 30 and most likely to be 25	Between 25 and 35 and most likely to be 30	Between 30 and 40 and most likely to be 35	Between 15 and 40	Between 14 and 25 and most likely to be 20	Between 20 and 30	Between 30 and 35 and most likely to be 33	Between 12 and 15	Between 20 and 30 and most likely to be 25	Between 15 and 25
	Acquisitions of photo service		Between 25 and 30	Between 12 and 28 and most likely to be 20	Between 16 and 27 and most likely to be 23	Between 10 and 15	Between 20 and 30	Between 15 and 30 and most likely to be 20	Between 10 and 20	Between 15 and 35	Between 20 and 40 and most likely to be 30	Between 10 and 15	Between 5 and 15 and most likely to be 10	Between 20 and 30
	Buying coals		Between 10 and 20 and most	Between 4 and 13	Between 15 and 30	Between 5 and 12	Between 8 and 15 and most	Between 10 and 15 and most	Between 10 and 15	Between 10 and 20	Between 15 and 25 and most	Between 5 and 10	Between 20 and 30	Between 15 and 30

			likely to be 15				likely to be 10	likely to be 13			likely to be 20			
	Buying foods and other things used in home		Between 30 and 42	Between 24 and 30	Between 20 and 30 and most likely to be 25	Between 25 and 40 and most likely to be 30	Between 30 and 35	Between 20 and 40 and most likely to be 30	Between 25 and 35	Between 20 and 50 and most likely to be 30 and 40	Between 20 and 30	Between 10 and 30 and most likely to be 20	Between 30 and 40	Between 20 and 30
	The selling and buying capacities		Between 30 and 45	Betwee n 25 and 35	Betwee n 30 and 40	Betwee n 30 and 40 and most likely 35	Betwee n 65 and 80	Betwee n 70 and 80	Between 50 and 60	Between 50 and 70 and most likely 60	Betwee n 55 and 65	Betwee n 30 and 50	Betwee n 35 and 45	Betwee n 50 and 55
	The standard of living		Between 65 and 75 and most likely 70	Betwee n 50 and 60	Betwee n 40 and 70 and	Betwee n 45 and 55	Betwee n 55 and 65	Betwee n 40 and 60 and	Between 35 and 45	Between 50 and 80 and	Betwee n 40 and 45	Betwee n 40 and 60	Betwee n 50 and 60	Betwee n 45 and 60

					most likely 55			most likely 50		most likely 60					
Marketing	The access to trading centres	The number of people affected	Between 40 and 80 and most likely between 55 and 65	Between 55 and 70	Between 50 and 70 and most likely to be 60	Between 45 and 60 and most likely to be 50	Between 50 and 80	Between 60 and 70	Between 45 and 55	Between 30 and 60	Between 50 and 70	Between 30 and 40	Between 20 and 50 and most likely to be 40	Between 30 and 50
	Potential trading opportunities		Between 50 and 70	Between 30 and 50	Between 50 and 60	Between 40 and 60	Between 50 and 80 and most likely to be 65	Between 45 and 65	Between 50 and 70 and most likely to be 70	Between 40 and 70	Between 60 and 70	Between 20 and 50	Between 50 and 60	Between 40 and 50
1.2 The number of days in this year the village will be prevented from access to district centre		No. of days	Between 15 and 20	Between 10 and 30 and most	Between 20 and 25	Between 20 and 40 and most	Between 30 and 40	Between 30 and 50 and most	Between 10 and 15	Between 20 and 25 and most	Between 10 and 20	Between 20 and 30	Between 20 and 25	Between 10 and 15

			likely to be 20		likely to be 30		likely to be 40		likely to be 23				

Sensitivity:

Questions		**Units**	**Expert No.**	**Expert type**	**Village name**			
					Ganyan	**Xiniu**	**Xiawu**	**Shuiying**
1 Productive assets								
		%	1	Sociologist	Between 30% and 40%	Between 35% and 55%	Between 30% and 45%	Between 25% and 40%

1.1 Land use	Arable farmland		2		Between 30% and 50% and most likely to be 40%	Between 20% and 40% and most likely to be 30%	Between 25% and 35%	Between 30% and 50%
			3		Between 40% and 60% and most likely to be 50%	Between 35% and 50%	Between 30% and 50% and most likely to be 40%	Between 40% and 45%
			4		Between 40% and 50%	Between 30% and 50%	Between 20% and 40%	Between 35% and 55%
	Pasture	%	1	Sociologist	Between 15% and 20%	Between 20% and 30%	Between 10% and 20%	Between 15% and 20%
			2		Between 10% and 20% and most likely to be 15%	Between 30% and 35%	Between 10% and 15%	Between 10% and 20%
			3		Between 10% and 15%	Between 20% and 40% and most likely to be 30%	Between 20% and 30%	Between 10% and 15%
			4		Between 20% and 25%	Between 30% and 40%	Between 10% and 20%	Between 20% and 30%

1.2 Income source	Farming	%	1	Sociologist	Between 60% and 70%	Between 50% and 60%	Between 40% and 50%	Between 40% and 50%
			2		Between 50% and 60% and most likely to be 55%	Between 40% and 60% and most likely to be 50%	Between 50% and 60%	Between 40% and 60%
			3		Between 40% and 50%	Between 35% and 40%	Between 50% and 70% and most likely to be 60%	Between 50% and 55%
			4		Between 50% and 70% and most likely to be 60%	Between 30% and 50% and most likely to be 40%	Between 60% and 70%	Between 50% and 60%
	Livestock	%	1	Sociologist	Between 20% and 30%	Between 25% and 35%	Between 30% and 35%	Between 20% and 30%
			2		Between 20% and 40% and most likely to be 30%	Between 30% and 40%	Between 15% and 30%	Between 40% and 50%
			3		Between 10% and 30% and most likely to be 20%	Between 20% and 30% and most likely to be 35%	Between 20% and 25%	Between 30% and 40%

			4		Between 20% and 30%	Between 20% and 40%	Between 30% and 40%	Between 20 and 40%
2 Collective assets								
2.1 Road route users								
The number of road route user from the village to district centre		No.	1	Rural road manager	Between 65 and 80	Between 100 and 120	Between 85 and 90	Between 75 and 95
			2		Between 50 and 70	Between 80 and 90	Between 90 and 110	Between 80 and 100
			3		Between 60 and 80	Between 85 and 100	Between 80 and 100	Between 80 and 90
2.2 Transporting passenger service								

A. Bicycle	No.	1	Sociologist	Between 20 and 30	Between 15 and 20	Between 24 and 36	Between 34 and 54
		2		Between 20 and 40 and most likely to be 30	Between 10 and 30 and most likely to be 20	Between 20 and 40 and most likely to be 30	Between 38 and 45
		3		Between 30 and 50	Between 10 and 20	Between 40 and 50	Between 49 and 67
		4		Between 20 and 40	Between 15 and 20	Between 30 and 50	Between 40 and 56
	No. of trips/day	1	Sociologist	Between 2 and 5 and most likely to be 3	Between 1 and 5	Between 2 and 4	Between 4 and 10
		2		Between 1 and 3	Between 3 and 6 and most likely to be 5	Between 2 and 8	Between 2 and 4
		3		Between 1 and 5 and most likely between 2 and 3	Between 2 and 4	Between 1 and 2	Between 2 and 8

		4		Between 2 and 3	Between 4 and 8	Between 2 and 4	Between 6 and 10
	Maximum No. of people/trip	1	Sociologist	2	2	2	2
		2		2	2	2	2
		3		2	2	2	2
		4		2	2	2	2
	No. of days in a year it can use	1	Sociologist	366	366	366	366
		2		366	366	366	366

		3		366	366	366	366
		4		366	366	366	366
B. Motorcycle	No.	1	Sociologist	Between 22 and 48 and most likely to be 33	Between 50 and 80 and most likely to be 65	Between 30 and 55	Between 47 and 53
		2		Between 30 and 50	Between 30 and 60 and most likely between 40 and 50	Between 25 and 43	Between 38 and 48
		3		Between 20 and 55	Between 50 and 60	Between 31 and 52	Between 52 and 64
		4		Between 25 and 40	Between 30 and 60 and most likely between 40 and 50	Between 28 and 38	Between 42 and 57
		1	Sociologist	Between 3 and 5	Between 2 and 6	Between 2 and 3	Between 4 and 6

	No. of trips/day	2		Between 1 and 5	Between 2 and 8	Between 1 and 4	Between 5 and 7
		3		Between 3 and 8	Between 4 and 10	Between 2 and 5	Between 3 and 5
		4		Between 3 and 6	Between 2 and 4	Between 3 and 4	Between 2 and 3
	Maximum No. of people/trip	1	Sociologist	2	2	2	2
		2		2	2	2	2
		3		2	2	2	2
		4		2	2	2	2

	No. of days in a year it can use	1	Sociologist	366	366	366	366
		2		366	366	366	366
		3		366	366	366	366
		4		366	366	366	366
C. Motorised Tricycle	No.	1	Sociologist	Between 5 and 15	Between 5 and 15	Between 10 and 15	Between 13 and 27
		2		Between 20 and 30 and most likely to be 25	Between 10 and 20 and most likely to be 15	Between 25 and 33	Between 18 and 31
		3		Between 10 and 30	Between 20 and 30 and most likely to be 25	Between 21 and 25	Between 16 and 23

		4		Between 15 and 20	Between 5 and 15	Between 18 and 23	Between 20 and 32
	No. of trips/day	1	Sociologist	Between 1 and 2	Between 1 and 2	Between 1 and 2	Between 2 and 3
		2		Between 2 and 5	Between 2 and 3	Between 1 and 2	Between 1 and 7
		3		Between 1 and 2	Between 1 and 2	Between 1 and 3	Between 2 and 3
		4		Between 1 and 5	Between 1 and 2	Between 2 and 5	Between 3 and 8
	Maximum No. of people/trip	1	Sociologist	3	3	3	3
		2		3	3	3	3

		3		3	3	3	3
		4		3	3	3	3
	No. of days in a year it can use	1	Sociologist	Between 346 and 350	Between 326 and 346	Between 350 and 356	Between 336 and 346
		2		Between 336 and 356	Between 326 and 336	Between 340 and 346	Between 340 and 346
		3		Between 340 and 346	Between 316 and 336	Between 346 and 356	Between 350 and 356
		4		Between 335 and 350	Between 325 and 336	Between 330 and 345	Between 325 and 335
D. Private Car	No.	1	Sociologist	Between 31 and 57	Between 30 and 50	Between 37 and 43	Between 51 and 67

		2		Between 50 and 76	Between 58 and 60	Between 52 and 63	Between 43 and 54
		3		Between 45 and 50	Between 40 and 52	Between 46 and 54	Between 49 and 62
		4		Between 32 and 56	Between 35 and 50	Between 50 and 55	Between 50 and 60 and most likely to be 55
	No. of trips/day	1	Sociologist	Between 2 and 4	Between 4 and 8 and most likely to be 6	Between 2 and 4	Between 1 and 4
		2		Between 4 and 8	Between 4 and 6	Between 6 and 8	Between 2 and 5
		3		Between 4 and 10 and most likely between 6 and 8	Between 2 and 4	Between 4 and 6	Between 4 and 6
		4		Between 4 and 8	Between 2 and 10 and most likely to be 6	Between 2 and 4	Between 2 and 6

	Maximum No. of people/trip	1	Sociologist	5	5	5	5
		2		5	5	5	5
		3		5	5	5	5
		4		5	5	5	5
	No. of days in a year it can use	1	Sociologist	Between 346 and 350	Between 326 and 346	Between 350 and 356	Between 336 and 346
		2		Between 336 and 356	Between 326 and 336	Between 340 and 346	Between 340 and 346
		3		Between 340 and 346	Between 316 and 336	Between 346 and 356	Between 350 and 356

		4		Between 335 and 350	Between 325 and 336	Between 330 and 345	Between 325 and 335
E. Bus	No.	1	Sociologist	Between 3 and 7	Between 2 and 4	Between 2 and 3	Between 4 and 6
		2		Between 5 and 10	Between 2 and 5	Between 2 and 3	Between 5 and 8
		3		Between 5 and 10 and most likely to be 7	Between 3 and 4	Between 3 and 5	Between 3 and 5
		4		Between 5 and 8	Between 2 and 3	Between 3 and 4	Between 3 and 7
	No. of trips/day	1	Sociologist	Between 1 and 2	Between 1 and 2	Between 1 and 2	Between 1 and 2
		2		Between 1 and 2	Between 1 and 2	Between 1 and 2	Between 1 and 2

		3		Between 1 and 2	Between 1 and 2	Between 1 and 2	Between 1 and 2
		4		Between 1 and 2	Between 1 and 2	Between 1 and 2	Between 1 and 2
	Maximum No. of people/trip	1	Sociologist	9	9	9	9
		2		9	9	9	9
		3		9	9	9	9
		4		9	9	9	9
		1	Sociologist	Between 346 and 350	Between 326 and 346	Between 350 and 356	Between 336 and 346

	No. of days in a year it can serve the village	2		Between 336 and 356	Between 326 and 336	Between 340 and 346	Between 340 and 346
		3		Between 340 and 346	Between 316 and 336	Between 346 and 356	Between 350 and 356
		4		Between 335 and 350	Between 325 and 336	Between 330 and 345	Between 325 and 335
2.3 Transporting cargo service							
F. Wheelbarrow	No.	1	Sociologist	Between 50 and 126	Between 50 and 80	Between 55 and 78	Between 37 and 63
		2		Between 53 and 70	Between 40 and 100 and most likely between 60 and 80	Between 64 and 83	Between 58 and 72
		3		Between 60 and 140 and most likely between 80 and 120	Between 60 and 80 and most likely to be 70	Between 58 and 73	Between 41 and 57

		4		Between 69 and 87	Between 70 and 90	Between 76 and 85	Between 53and 59
	No. of trips/day	1	Sociologist	Between 1 and 2	Between 1 and 2	Between 1 and 2	Between 3 and 4
		2		Between 1 and 5	Between 1 and 3	Between 1 and 2	Between 2 and 5
		3		Between 2 and 3	Between 3 and 5	Between 1 and 2	Between 1 and 3
		4		Between 1 and 2	Between 2 and 5	Between 1 and 2	Between 2 and 3
	Maximum loads (kg)/trip	1	Sociologist	100	100	100	100
		2		100	100	100	100

		3		100	100	100	100
		4		100	100	100	100
	No. of days in a year it can use	1	Sociologist	366	366	366	366
		2		366	366	366	366
		3		366	366	366	366
		4		366	366	366	366
	No.	1	Sociologist	Between 15 and 20	Between 35 and 45	Between 23 and 31	Between 17 and 28

I. Animal Drawn Cart		2		Between 10 and 30 and most likely to be 20	Between 30 and 60 and most likely between 40 and 50	Between 18 and 26	Between 26 and 40
		3		Between 10 and 15	Between 20 and 40 and most likely to be 30	Between 12 and 18	Between 30 and 40
		4		Between 10 and 20 and most likely to be 15	Between 20 and 30	Between 10 and 30	Between 15 and 26
	No. of trips/day	1	Sociologist	Between 2 and 3	Between 1 and 2	Between 2 and 4	Between 3 and 6
		2		Between 1 and 6	Between 1 and 2	Between 1 and 4	Between 1 and 3
		3		Between 5 and 6	Between 1 and 3	Between 3 and 5	Between 2 and 8
		4		Between 1 and 3	Between 1 and 2	Between 1 and 3	Between 5 and 10

	Maximum loads(kg)/trip	1	Sociologist	350	350	350	350
		2		350	350	350	350
		3		350	350	350	350
		4		350	350	350	350
	No. of days in a year it can serve the village	1	Sociologist	Between 346 and 350	Between 326 and 346	Between 350 and 356	Between 336 and 346
		2		Between 336 and 356	Between 326 and 336	Between 340 and 346	Between 340 and 346
		3		Between 340 and 346	Between 316 and 336	Between 346 and 356	Between 350 and 356

		4		Between 335 and 350	Between 325 and 336	Between 330 and 345	Between 325 and 335
J. Tractor	No.	1	Sociologist	Between 3 and 7	Between 10 and 13	Between 5 and 8	Between 5 and 10
		2		Between 5 and 6	Between 3 and 7	Between 7 and 10	Between 4 and 8
		3		Between 2 and 8	Between 5 and 10	Between 5 and 10	Between 6 and 9
		4		Between 5 and 7	Between 4 and 5	Between 3 and 6	Between 8 and 10
	No. of trips/day	1	Sociologist	Between 1 and 2	Between 2 and 4	Between 1 and 2	Between 1 and 2
		2		Between 2 and 3	Between 1 and 3	Between 2 and 3	Between 2 and 4

		3		Between 1 and 3 and most likely to be 2	Between 1 and 2	Between 1 and 3	Between 2 and 5
		4		Between 2 and 3	Between 1 and 2	Between 3 and 5	Between 1 and 4
	Maximum loads(kg)/trip	1	Sociologist	700	700	700	700
		2		700	700	700	700
		3		700	700	700	700
		4		700	700	700	700
		1	Sociologist	Between 346 and 350	Between 326 and 346	Between 350 and 356	Between 336 and 346

	No. of days in a year it can serve the village	2		between 336 and 356	Between 326 and 336	between 340 and 346	Between 340 and 346
		3		between 340 and 346	between 316 and 336	between 346 and 356	Between 350 and 356
		4		Between 335 and 350	Between 325 and 336	between 330 and 345	between 325 and 335
K. Mini Lorry	No.	1	Sociologist	Between 2 and 5	Between 3 and 7	Between 2 and 4	Between 3 and 6
		2		Between 2 and 7	Between 5 and 8	Between 5 and 7	Between 2 and 5
		3		Between 1 and 3	Between 5 and 10	Between 3 and 8	Between 5 and 6
		4		Between 3 and 8 and most likely to be 6	Between 3 and 8	Between 8 and 10	Between 1 and 6

	No. of trips/day	1	Sociologist	Between 0.5 and 2	Between 0.5 and 1	Between 1 and 2	Between 0.5 and 2
		2		Between 1 and 2	Between 0.5 and 1.5	Between 0.5 and 1	Between 1 and 2
		3		Between 0.5 and 1	Between 1 and 2	Between 0.5 and 1	Between 1 and 1.5
		4		Between 1 and 2	Between 0.5 and 1	Between 1 and 3	Between 0.5 and 1
	Maximum loads(kg)/trip	1	Sociologist	1000	1000	1000	1000
		2		1000	1000	1000	1000
		3		1000	1000	1000	1000

		4		1000	1000	1000	1000
	No. of days in a year it can serve the village	1	Sociologist	Between 346 and 350	Between 326 and 346	Between 350 and 356	between 336 and 346
		2		between 336 and 356	Between 326 and 336	between 340 and 346	Between 340 and 346
		3		between 340 and 346	between 316 and 336	between 346 and 356	Between 350 and 356
		4		Between 335 and 350	Between 325 and 336	between 330 and 345	between 325 and 335
L. Lorry	No.	1	Sociologist	Between 1 and 5	Between 1 and 4	Between 2 and 3	Between 3 and 5
		2		Between 3 and 4	Between 1 and 5	Between 2 and 4 and most likely to be 3	Between 2 and 4

		3		Between 1 and 3	Between 1 and 3	Between 1 and 2	Between 1 and 5
		4		Between 5 and 6	Between 2 and 3	Between 3 and 7	Between 1 and 3
	No. of trips/day	1	Sociologist	Between 0.2 and 0.3	Between 0.1 and 0.2	Between 0.2 and 0.3	Between 0.1 and 0.2
		2		Between 0.1 and 0.2	Between 0.2 and 0.3	Between 0.1 and 0.2	Between 0.1 and 0.3
		3		Between 0.2 and 0.3	Between 0.1 and 0.4	Between 0.1 and 0.3	Between 0.2 and 0.4
		4		Between 0.2 and 0.6	Between 0.1 and 0.3	Between 0.1 and 0.2	Between 0.3 and 0.4
		1	Sociologist	5000	5000	5000	5000

	Maximum loads(kg)/trip	2		5000	5000	5000	5000
		3		5000	5000	5000	5000
		4		5000	5000	5000	5000
	No. of days in a year it can serve the village	1	Sociologist	Between 346 and 350	Between 326 and 346	Between 350 and 356	Between 336 and 346
		2		Between 336 and 356	Between 326 and 336	Between 340 and 346	Between 340 and 346
		3		Between 340 and 346	Between 316 and 336	Between 346 and 356	Between 350 and 356
		4		Between 335 and 350	Between 325 and 336	Between 330 and 345	Between 325 and 335

3 Stores							
3.1 How many day in this year the village's store cannot satisfy food needs	No.	1	Sociologist	Between 32 and 41	Between 60 and 70	Between 55 and 63	Between 30 and 60
		2		Between 26 and 34	Between 30 and 60 and most likely between 40 and 50	Between 43 and 60	Between 20 and 40
		3		Between 20 and 50 and most likely to be 35	Between 40 and 50	Between 37 and 64	Between 35 and 55
		4		Between 10 and 25	Between 36 and 50	Between 28 and 45	Between 40 and 45
4 Claims							
	No.	1	Sociologist	Between 34 and 50	Between 50 and 70 and most likely to be 60	Between 54 and 76	Between 42 and 65

4.1 How many village members in this year cannot require assistance		2		Between 37 and 43	Between 44 and 52	Between 82 and 94	Between 53 and 88
		3		Between 50 and 60	Between 47 and 72	Between 47 and 83	Between 60 and 80
		4		Between 47 and 89	Between 50 and 60	Between 55 and 65	Between 48 and 77

5 IRI estimation for road routes						
Ganyan village						
Road route name	**Video No.**	**Start km**	**End km**	**Visual description**	**Academic 1 (m/km)**	**Academic 2 (m/km)**

Ganyan -- Changchunpu	1	0	1+000	Occasional shallow-moderate depressions	Between 4 and 5 and most likely between 4.3 and 4.6	Between 4 and 5 and most likely between 4.0 and 4.5
Ganyan -- Changchunpu	2	1+000	2+000	Occasional depressions	Between 4 and 6 and most likely between 4.7 and 5.3	Between 4 and 5 and most likely between 4.5 and 5
Ganyan -- Changchunpu	3	2+000	3+000	Occasional depressions	Between 3.5 and 4.5 and most likely between 3.8 and 4.2	Between 4 and 5 and most likely between 4.5 and 5
Ganyan -- Changchunpu	4	3+000	4+000	Occasional moderate depressions, potholes and patching	Between 5 and 7 and most likely between 5.8 and 6.2	Between 6 and 7 and most likely between 6.5 and 7
Xiniu village						
Road route name	**Video No.**	**Start km**	**End km**	**Visual description**	**Academic 1 (m/km)**	**Academic 2 (m/km)**

Xiniu -- Changchunpu	1	0	1+000	Occasional depressions	Between 3.8 and 4.8 and most likely between 4.2 and 4.4	Between 4 and 5 and most likely between 4.5 and 5
Xiniu -- Changchunpu	2	1+000	2+000	Moderate shallow depressions and potholes	Between 5 and 8 and most likey between 5.5 and 7.5	Between 7 and 8 and most likely between 7.0 and 7.5
Xiniu -- Changchunpu	3	2+000	3+000	Occasional depressions and potholes	Between 3.5 and 5 and most likely between 4.1 and 4.5	Between 6 and 7 and most likely between 6.5 and 7
Xiniu -- Changchunpu	4	3+000	3+400	Occasional depressions and potholes	Between 3.5 and 5 and most likely between 4.1 and 4.5	Between 6 and 7 and most likely between 6.5 and 7
Xiawu village						
Road route name	**Video No.**	**Start km**	**End km**	**Visual description**	**Academic 1 (m/km)**	**Academic 2 (m/km)**

Xiawu -- Changchunpu	1	0	1+000	Occasional depressions and potholes	Between 4.5 and 7 and most likely between 5.5 and 6	Between 6 and 7 and most likely between 6.5 and 7
Xiawu -- Changchunpu	2	1+000	2+000	Occasional depressions and potholes	Between 4 and 6 and most likely between 4.8 and 5.2	Between 5 and 6 and most likely between 5.5 and 6
Xiawu -- Changchunpu	3	2+000	3+000	Occasional depressions and potholes	Between 4.3 and 5.8 and most likely between 4.9 and 5.2	Between 5 and 6 and most likely between 5.5 and 6
Xiawu -- Changchunpu	4	3+000	3+900	Negligible depressions and no potholes	Between 3.6 and 5 and most likely between 4 and 4.4	Between 3 and 4 and most likely between 3.5 and 4
Shuiying village						
Road route name	**Video No.**	**Start km**	**End km**	**Visual description**	**Academic 1 (m/km)**	**Academic 2 (m/km)**

Xiawu -- Changchunpu	1	0	1+000	Occasional depressions and potholes	Between 4.2 and 5.2 and most likely between 4.6 and 4.8	Between 4 and 5 and most likely between 4.5 and 5
Xiawu -- Changchunpu	2	1+000	2+000	Negligible depressions and no potholes	Between 3.5 and 4.7 and most likely between 3.8 and 4.4	Between 4 and 5 and most likely between 4 and 4.5
Xiawu -- Changchunpu	3	2+000	3+000	Negligible depressions and no potholes	Between 3.8 and 4.9 and most likely between 4.1 and 4.6	Between 4 and 5 and most likely between 4 and 4.5
Xiawu -- Changchunpu	4	3+000	4+000	Negligible depressions and no potholes	Between 3.9 and 4.9 and most likely between 4.1 and 4.7	Between 4 and 5 and most likely between 4 and 4.5
Xiawu -- Changchunpu	5	4+000	5+000	Negligible depressions and no potholes	Between 3.9 and 4.9 and most likely between 4.1 and 4.7	Between 4 and 5 and most likely between 4 and 4.5
Xiawu -- Changchunpu	6	5+000	5+700	Negligible depressions and no potholes	Between 4 and 5 and most likely between 4.4 and 4.6	Between 4 and 5 and most likely between 4 and 4.5

Resilience:

Questions	**Units**		**Village name**			
		Rural road manager No.	**Ganyan**	**Xiniu**	**Xiawu**	**Shuiying**
1 Community participation/human resources						
Labourer	No.	1	between 25 and 40	between 31 and 44	between 48 and 72	between 18 and 34

		2	between 22 and 45	between 25 and 35	between 55 and 65	between 23 and 37
		3	Between 30 and 45	Between 35 and 50	Between 50 and 60	Between 25 and 40
Supervisor	No.	1	Between 2 and 7 and most likely to be between 4 and 5	Between 5 and 9	Between 7 and 11	Between 2 and 6
		2	Between 1 and 5	Between 4 and 6	Between 8 and 14	Between 3 and 7

		3	between 2 and 5	between 5 and 8	between 7 and 9	between 3 and 6
Technician	No.	1	Between 3 and 9 and most likely to be 6	Between 3 and 7	Between 4 and 7	Between 3 and 5
		2	Between 2 and 7	Between 3 and 5	Between 5 and 7	Between 2 and 8
		3	Between 4 and 7	Between 5 and 7	Between 4 and 10	Between 3 and 7
Monitoring	No.	1	Between 5 and 7	Between 2 and 6	Between 6 and 8	Between 4 and 6

		2	between 4 and 9	between 3 and 8	between 5 and 11	between 2 and 4
		3	between 5 and 10	between 4 and 8	between 5 and 8	between 3 and 5

Appendix F: Expert opinions on model verification

Participant 1:

Q1: The following table demonstrate the exposure ranking for four villages considered.

Relative ranking for exposure	The most exposure	The second most exposure	The third most exposure	The least exposure
Village name	Xiniu village	Ganyan village	Shuiying village	Xiawu village

Do you agree with the ranking?

Yes ☒

No ☐

If no, please give your comments

Q2: The following table demonstrate the sensitivity ranking for four villages considered.

Relative ranking for sensitivity	The most sensitivity	The second most sensitivity	The third most sensitivity	The least sensitivity
Village name	Xiawu village	Xiniu village	Shuiying village	Ganyan village

Do you agree with the ranking?

Yes [×]

No [ ]

If no, please give your comments

Q3: The following table demonstrate the resilience ranking for four villages considered

Relative ranking for resilience	The most resilience	The second most resilience	The third most resilience	The least resilience
Village name	Ganyan village	Xiniu village	Shuiying village	Xiawu village

Do you agree with the ranking?

Yes ☒

No ☐

If no, please give your comments

Q4: The following table demonstrate the vulnerability ranking for four villages considered.

Relative ranking for vulnerability	The most vulnerability	The second most vulnerability	The third most vulnerability	The least vulnerability
Village name	Xiawu village	Xiniu village	Shuiying village	Ganyan village

Do you agree with the ranking?

Yes ☒

No ☐

If no, please give your comments

Participant 2:

Q1: The following table demonstrate the exposure ranking for four villages considered.

Relative ranking for exposure	The most exposure	The second most exposure	The third most exposure	The least exposure
Village name	Xiniu village	Ganyan village	Shuiying village	Xiawu village

Do you agree with the ranking?

Yes [×]

No [ ]

If no, please give your comments

Q2: The following table demonstrate the sensitivity ranking for four villages considered.

Relative ranking for sensitivity	The most sensitivity	The second most sensitivity	The third most sensitivity	The least sensitivity
Village name	Xiawu village	Xiniu village	Shuiying village	Ganyan village

Do you agree with the ranking?

Yes ☒

No ☐

If no, please give your comments

Q3: The following table demonstrate the resilience ranking for four villages considered

Relative ranking for resilience	The most resilience	The second most resilience	The third most resilience	The least resilience
Village name	Ganyan village	Xiniu village	Shuiying village	Xiawu village

Do you agree with the ranking?

Yes ☒

No ☐

If no, please give your comments

Q4: The following table demonstrate the vulnerability ranking for four villages considered.

Relative ranking for vulnerability	The most vulnerability	The second most vulnerability	The third most vulnerability	The least vulnerability
Village name	Xiawu village	Xiniu village	Shuiying village	Ganyan village

Do you agree with the ranking?

Yes ☒

No ☐

If no, please give your comments

<u>Participant 3:</u>

Q1: The following table demonstrate the exposure ranking for four villages considered.

Relative ranking for exposure	The most exposure	The second most exposure	The third most exposure	The least exposure
Village name	Xiniu village	Ganyan village	Shuiying village	Xiawu village

Do you agree with the ranking?

Yes ☒

No ☐

If no, please give your comments

Q2: The following table demonstrate the sensitivity ranking for four villages considered.

Relative ranking for sensitivity	The most sensitivity	The second most sensitivity	The third most sensitivity	The least sensitivity
Village name	Xiawu village	Xiniu village	Shuiying village	Ganyan village

Do you agree with the ranking?

Yes ☒

☐

No

If no, please give your comments

Q3: The following table demonstrate the resilience ranking for four villages considered

Relative ranking for resilience	The most resilience	The second most resilience	The third most resilience	The least resilience
Village name	Ganyan village	Xiniu village	Shuiying village	Xiawu village

Do you agree with the ranking?

Yes ☒

No ☐

If no, please give your comments

Q4: The following table demonstrate the vulnerability ranking for four villages considered.

Relative ranking for vulnerability	The most vulnerability	The second most vulnerability	The third most vulnerability	The least vulnerability
Village name	Xiawu village	Xiniu village	Shuiying village	Ganyan village

Do you agree with the ranking?

Yes ☒

No ☐

If no, please give your comments

Participant 4:

Q1: The following table demonstrate the exposure ranking for four villages considered.

Relative ranking for exposure	The most exposure	The second most exposure	The third most exposure	The least exposure

Village name	Xiniu village	Ganyan village	Shuiying village	Xiawu village

Do you agree with the ranking?

Yes ☒

No ☐

If no, please give your comments

Q2: The following table demonstrate the sensitivity ranking for four villages considered.

Relative ranking for sensitivity	The most sensitivity	The second most sensitivity	The third most sensitivity	The least sensitivity

Village name	Xiawu village	Xiniu village	Shuiying village	Ganyan village

Do you agree with the ranking?

Yes ☒

No ☐

If no, please give your comments

Q3: The following table demonstrate the resilience ranking for four villages considered

Relative ranking for resilience	The most resilience	The second most resilience	The third most resilience	The least resilience
Village name	Ganyan village	Xiniu village	Shuiying village	Xiawu village

Do you agree with the ranking?

Yes ☒

No ☐

If no, please give your comments

Q4: The following table demonstrate the vulnerability ranking for four villages considered.

Relative ranking for vulnerability	The most vulnerability	The second most vulnerability	The third most vulnerability	The least vulnerability
Village name	Xiawu village	Xiniu village	Shuiying village	Ganyan village

Do you agree with the ranking?

Yes [X]

No [ ]

If no, please give your comments

Appendix G: MATLAB© code for implementing fuzzy rule-based system

```
[System]
Name='Vulnerability2'
Type='mamdani'
Version=2.0
NumInputs=3
NumOutputs=1
NumRules=125
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input1]
Name='Exposure'
Range=[0 1]
NumMFs=5
MF1='very_low':'trapmf',[0 0 0.27 0.42]
MF2='low':'trapmf',[0.27 0.42 0.57 0.65]
MF3='moderate':'trapmf',[0.57 0.65 0.8 0.88]
MF4='high':'trapmf',[0.8 0.88 0.96 1]
MF5='very_high':'trapmf',[0.96 1 1 1]

[Input2]
Name='Sensitivity'
Range=[0 1]
NumMFs=5
```

MF1='very_low':'trapmf',[0 0 0.27 0.42]
MF2='low':'trapmf',[0.27 0.42 0.57 0.65]
MF3='moderate':'trapmf',[0.57 0.65 0.8 0.88]
MF4='high':'trapmf',[0.8 0.88 0.96 1]
MF5='very_high':'trapmf',[0.96 1 1 1]

[Input3]
Name='Resilience'
Range=[0 1]
NumMFs=5
MF1='very_high':'trapmf',[0 0 0.27 0.42]
MF2='high':'trapmf',[0.27 0.42 0.57 0.65]
MF3='modetate':'trapmf',[0.57 0.65 0.8 0.88]
MF4='low':'trapmf',[0.8 0.88 0.96 1]
MF5='very_low':'trapmf',[0.96203873598369 1.00203873598369 1.00203873598369 1.00203873598369]

[Output1]
Name='Vulnerability'
Range=[0 1]
NumMFs=5
MF1='very_low':'trapmf',[0 0 0.27 0.42]
MF2='low':'trapmf',[0.27 0.42 0.57 0.65]
MF3='moderate':'trapmf',[0.57 0.65 0.8 0.88]
MF4='high':'trapmf',[0.8 0.88 0.96 1]
MF5='very_high':'trapmf',[0.96 1 1 1]

[Rules]
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5 4 5, 5 (1) : 1
5 3 5, 5 (1) : 1

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