

Residential electrification design topology evaluation model - The sustainable approach for residential developments

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Dissertation accepted in fulfilment of the requirements for the
degree *Master of Engineering in Development and
Management Engineering* at the North West University

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Graduation: May 2020

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PREFACE

I would like to thank Professor Wichers for the continuous support, guidance and insight in the compilation of this dissertation. I would profoundly like to thank Oom Hercules Ferreira, a now retired industry specialist, who is the person who first introduced me to the concept of sustainable electrification designs and the thought process involved which instilled my desire for having long term electrification design vision. I would also like to thank my first professional development mentor, Johan Pieters for providing me with a platform to commence with my consulting career, his guidance and contribution in my professional development. I would like to extend the greatest gratitude to Corrie van der Wath, the executive team and the entire family of both Matleng Energy Solutions and Pendo Energy Solutions for the daily support, out of the box thinking, smart business orientated thought processes, strategic guidance, transparency, conversations, general life discussions, laughs, jokes and the wonderful working environment as this is the place I spend a third of my day! Thank you to my little nana for the time spent proof-reading the dissertation. A big word of thank you to my supportive parents and my late grandparents who provided the foundation together with the wisdom for the person I am to this day.

Above all, I would like to thank the God All Mighty for all that He has blessed me with –
Ngiyabonga!

ABSTRACT

Residential development electrification is a key societal element which signifies development in developing countries. The impact of the residential development needs to cater not only for the current needs, but consider the future needs of the upcoming generations. Issues of importance which govern these residential developments are the decisions which are taken during the planning phases. It is thus, with this context in mind that this dissertation seeks to provide a tool in the form of an evaluation model to aid electrical supply authorities and developers on the decision of the applicable electrical design topology implemented in residential developments. The model is developed from a consultancy perspective as a working tool in order to increase profitability and to rationalise the decision on the network design topology to be implemented in residential developments.

The criteria used in the evaluation model shall firstly ensure that the load requirements of the development are fulfilled and incorporate elements of sustainability throughout the electrical infrastructure life cycle. A review of the paths taken by developed nations and lessons applicable to the particular design environment shall form part of this document. The Analytical Hierarchy Process (AHP) shall be adopted with the implementation of the evaluation model. AHP is a multi-criteria decision-making methodology which uses pair-wise comparison to determine a logical objective. On the successful completion of the evaluation model, a simple to use, user friendly Microsoft Excel decision-making tool shall be available to use for achieving sustainable electrification design decisions.

Keywords: Electrification, Evaluation Model, Sustainability, Analytical Hierarchy Process (AHP)

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LIST OF ACRONYMS

A	Amperes
AAAC	All Aluminium Alloy Conductor
ABC	Aerial Bundle Conductor
AC	Alternating Current
ACSR	Aluminium Conductor Steel Reinforced
ADMD	After Diversity Maximum Demand
AHP	Analytical Hierarchy Process
Al	Aluminium
AMEU	Association of Municipal Electricity Utilities
AS/NZS	Australian / New Zealand Standard
CAIDI	Customer Average Interruption Duration Index
CI	Consistency Index
CIED	Congrès International des Réseaux Electriques de Distribution
CR	Consistency Ratio
CSIR	Council for Scientific and Industrial Research
Cu	Copper
DC	Direct Current
DSTA	Double Steel Tape Armour
ECO10	Economy 10
ECSA	Engineering Council of South Africa
EMF	Electromagnetic Fields
ED1	Electricity Distribution 1 (United Kingdom Regulatory Framework – Price Control Period from 01 April 2015 to 31 March 2023)
FLISP	Finance Linked Individual Subsidy Programme
GSWA	Galvanised Steel Wire Armour
GUI	Graphical User Interface
HH	Household
HV	High Voltage
IEEE	Institute of Electrical and Electronic Engineers
IET	Institute of Engineering and Technology
INEP	Integrated National Electrification Programme
kW	kiloWatt
kV	kiloVolt
kVA	kiloVolt Ampere
LSM	Living Standard Measure

LV	Low Voltage
LV ABC	Low Voltage Aerial Bundle Conductor
MD	Maximum Demand
MSS	Miniature Substation
MV	Medium Voltage
MVA	MegaVolt Ampere
MV ABC	Medium Voltage Aerial Bundle Conductor
MW	MegaWatt
NEC	National Electrical Code
NERSA	National Energy Regulator of South Africa
NFPA	National Fire Protection Association
NRS	National Rationalised Specification
PILC	Paper Insulated Lead Covered
PVC	Polyvinyl Chloride
PVC LV	Polyvinyl Chloride Low Voltage
R1	Residential 1
RDP	Reconstruction and Development Programme
RIIO	Revenue = Incentives + Innovation + Outputs (United Kingdom Regulatory Framework)
S/S	Substation
SAARF	South African Audience Research Foundation
SABS	South African Bureau of Standards
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SANS	South African National Standards
SF6	Sulphur Hexafluoride
SOC (Ltd)	State Owned Company Limited
SWA	Steel Wire Armour
TRF	Transformer
U/G	Underground
URDS	Underground Residential Distribution System
URMC	Un-Restricted Medium Consumption
USDG	Urban Settlement Development Grant
V	Volts
VA	Volt Ampere
VBA	Visual Basic for Applications
WCED	World Commission on Environment and Development

XLPE

Cross Linked Polyethylene

NOMENCLATURE

$^{\circ}\text{C}$	Degree Celsius
α	Alpha Parameter of Beta Probability Density Function
β	Beta Parameter of Beta Probability Density Function
c	Consumer Circuit Breaker Size
σ	Standard Deviation of Consumer Load Data
σ^2	Statistical Variance of Consumer Load Data
μ	Mean of Consumer Load Data
A	Starting Point of the S curve
B	Number of Years until Saturation
C	Number between 1 and 10; 1 = Strong Initial Growth and 10 = Slow Initial Growth
C_i	Initial Investment Costs (Planning-Design and Construction)
$C_{\text{comparison}}$	Check Comparison Matrix
C_d	Decommissioning Costs
C_{om}	Operations and Maintenance Costs
CI	Consistency Index
$CI_{\text{random sample}}$	Consistency Index of a Random Sample
DCF	Diversity Correction Factor
EigenColumn	Eigen Column Matrix
f	Gompertz Curve Function
k	Coincidence Factor
$\text{Lamda}_{\text{max}}$	Lamda Column Matrix
LCC	Life Cycle Costing
N	Number of Homogenous Consumers
n	Order of Comparison Matrix
$P_{\text{performance}}$	Performance Matrix
$p(x)$	Beta Probability Density Function ($0 < x < 1$)
$R_{\text{NetworkTopologyRanking}}$	Network Topology Ranking Column Matrix
$R(\text{SA})_{\text{NetworkTopologyRankingSensitivityAnalysis}}$	Network Topology Ranking Column Matrix
$W_{\text{Financial}}$	Weight of Financial Criterion
$W_{\text{Reliability}}$	Weight of Reliability Criterion
$W_{\text{Social \& Environmental}}$	Weight of Social & Environmental Criterion
$W_{\text{SAEqualWeights}}$	Sensitivity Analysis with Equal Weights of the Comparison Matrix

$W_{\text{SADifferentWeights}}$

$X_{\text{comparison}}$

Sensitivity Analysis with Highest Ranking Criteria Leading
and Remaining Two Alternatives Equal in Weight
Comparison Matrix

CHAPTER 1

1. INTRODUCTION AND PROBLEM STATEMENT

1.1 INTRODUCTION AND CONTEXT

Residential electrification was originally implemented through overhead electrical networks. Over time, developed nations lead the way with the implementation of residential electrification through underground electrical networks. The outcomes of residential electrification are embedded within the inherent principle of improving the quality of life and paves the way for opportunities emanating from access to electricity.

The decision on the manner with respect to the implementation of the residential electrification has been a contentious issue and argument for several decades (Brumby *et al.*, 2009:1; O'Brien & Thompson, 1966:85; Wen *et al.*, 2012:142) – the question is – underground or overhead residential electrification? Over the years a hybrid system which is a combination of the two primary systems has emerged (Mackevich, 1989:183). In most cases and more often than not, the decision on the system implemented has been influenced by preferences of the decision maker either being the supply authority or the developer, rather than the decision being exclusively based on the technical and economic ramifications through-out the life cycle of the electrical infrastructure.

The evaluation model to be developed seeks to provide a decision-making tool for residential development electrification. Developing the evaluation model is important since it shall eliminate uncertainties with the type of topology implemented in residential developments. The current generation is faced with challenges to develop innovative sustainable solutions in terms of electrical infrastructure development. The elements of sustainability comprising mainly of economic, environmental and social objectives are fundamental. This is of utmost importance as sustainability tends to seek a reasonable balance between these three elements. These are therefore necessary and shall need to be implemented through-out the project life cycle commencing with planning-design, construction, operations-maintenance and decommissioning. Residential electrification shall remain a need for the current generation and future generations to come.

The focus area of this dissertation shall be limited to the urban and township residential developments. Electrification in sparse and rural areas shall not be covered in this dissertation.

The primary driver of the evaluation model shall be the implementation of sustainable technical aspects primarily in the planning-design phase of the electrical infrastructure life cycle. The incorporation of sustainability principles through-out the electrical infrastructure life cycle is a fundamental requirement. Rational financial considerations on the basis of the technical aspects shall be part of the model as decisions need to be substantiated by just and logical business cases. The realisation of the electrical infrastructure shall be to provide long-term solutions – thus in the event of a phased residential development approach, the short-to-medium term objective shall need to be aligned with the overall development goals. This shall eradicate unjust and unnecessary ad-hoc residential development implementation.

1.2 PROBLEM STATEMENT

Towards the end of the 19th century and the beginning of the 20th century, there were indifferences with respect to electricity distribution, either direct current (DC) or alternating current (AC), this period was befittingly referred to as – the war of currents, with Thomas Edison the driver for DC and Nikola Tesla the driver for AC (Sulzberger, 2003a:65; Sulzberger, 2003b:71). Urbanisation continued, electricity distribution through AC took the forefront due to practicality, costs and safety. A recent comparison between AC and DC distribution systems is thoroughly investigated (Hammerstrom, 2007:3). Electrical distribution as well as residential electrification were implemented through overhead networks. In the 1960's the developed countries commenced with the implementation of underground networks and some years later, the emergence of hybrid systems made its way into the market.

The main issue at hand is deciding which electrification topology needs to be implemented in residential developments in urban and townships areas in order to provide sustainable electrical infrastructure. Is it either an underground network, an overhead network or a hybrid network design?

The decision on the implemented system needs to firstly meet the technical system development requirements, not only for the short term but for the long-term i.e. through-out the life cycle of the electrical infrastructure. The primary driver shall be the load requirement in terms of the development After Diversity Maximum Demand (ADMD) and system reliability. The financial viability of the system needs to be accounted for and furthermore social as well as environmental considerations need to be considered. Thus, finding a realistic and rational balance between these factors shall be a major proponent of this dissertation. With respect to the above, the problem to be researched is the Residential Electrification Design Topology Evaluation Model – The Sustainable Approach for Residential Developments.

1.3 RESEARCH BACKGROUND

In this section, recorded literature discussing the problem statement shall be thoroughly investigated. Since the late 1990's and early 2000's developed nations, namely the United States of America, Australia and countries in the European Union have spent a significant amount of time, resources and effort investigating feasible options of converting existing distribution overhead electrical networks to underground networks (Commission of the European Communities, 2003; Downey, 2001; Johnson, 2007; Maney, 1996:15).

A common trend in the findings of these reports is the high costs associated with the conversion process from the existing overhead network to underground network. The acquired benefits vary largely. Thus, it is the primary objective of this dissertation to provide the decision maker with the tool to make an informed and sustainable engineering decision taking into cognisance the factors contributing to the residential development over the electrical infrastructure life cycle. Though outside the scope of this dissertation, the Institute of Engineering and Technology (IET) performed a transmission network undergrounding report which had a cautionary note to compare the best practicable designs over the life cycle cost to aid the investment decision (Parsons Brinckerhoff & Cable Consulting International Limited, 2012).

It is thus the objective of this dissertation to learn from the events of previous documented activities to provide for sustainable and logical long-term decisions. The concept thrives to provide means for making decisions on the basis of sound technical, financial and social factors. An in-depth analysis of these factors shall be provided. These factors are to be subjectively compared and weighed against each other. An investigation into the drivers for:

- i) the developed nations effort to review and consider relocation of electrical services to underground.
- ii) the parameters which set to influence the ideology to have the electrical services underground.

This seeks to incorporate the responses to questions such as why underground network, why now the investigation on the option of Out of Sight – Out of Mind. For the life cycle of the electrical infrastructure, is the design worth the investment, who gets the most benefits? In an endeavour to furthermore dissect the problem statement – the factors which contribute to making an informed decision with regard to the development of the evaluation model shall be dealt with based on documented literature.

This seeks to form a basis to justify the need to understand the underlying principles in order to make a sustainable decision on the electrification topology implemented over the infrastructure life cycle.

1.3.1 Technical Requirements

In residential electrification design the objective of the technical requirements are to meet the primary objective which is to cater for the predicted load requirement. There has been numerous documented literature which covers the modelling and implementation of the electrical load requirement (Herman & Gaunt, 2008:2249; Melodic & Strbac, 2003:3; Yi, 2013). The problem of residential load estimation has been thoroughly investigated and continues to be investigated. Residential loads are modelled as constant current sources with the constraint variable being the voltage. The modelling of the residential loads has developed over the years initially emerging through the implementation of the deterministic approach.

Towards the turn of the century a concerted effort has been invested in the development of the probabilistic approach. It has been recorded that the probabilistic approach yields more accurate results predominately due to the stochastic nature of residential loads (Ferguson & Gaunt, 2003:3). On the basis of these two approaches studies have been performed to establish the optimal manner of designing residential electrification.

1.3.1.1 Load Requirement – Deterministic Approach

In residential load estimation insightful work has been performed from around the 1930's in order to develop formulae to determine and predict residential load. The journey commenced with a monumental discovery with the phenomena known as coincidence with its inverse defined as diversity (Bary, 1945:625). Coincidence is defined as the degree of likelihood that electrical appliances are switched on at the same time. This factor is always less than unity in normal load conditions – it is only in abnormal load conditions in which it can be equal to unity resulting in a phenomenon referred to as a “cold pick up” load. This is an event in which all electrical appliances are simultaneously switched on. Diversity on the other hand is always greater than unity. Diversity is defined as the sum of the system peak load over the individual peak sum of the different homogenous set of residential consumers.

The ADMD is defined as the average power maximum demand per consumers after the consideration of diversity for the specific number of consumers. The ADMD is a function of the number of consumers and it increases with a reduction in the number of customers (Boggis, 1953: 359).

It increases to a point where it flattens out (i.e. the deviation from the mean is minimal) due to the diversity tending towards unity as the number of consumers approaches infinity. It is important to note that ADMD is always defined for a set of homogenous consumers – in this case residential consumers.

The relationship between diversity, coincidence and the consumers' ADMD which is used to determine the development total residential load estimate is provided below:

$$MD = N \times DCF \times ADMD \quad \dots (1)$$

$$DCF = 1 + \frac{k}{N} \quad \dots (2)$$

$$ADMD = \lim_{n \rightarrow \infty} \frac{1}{N} \sum_{i=1}^n MD_i \quad \dots (3)$$

Where the development Maximum Demand (MD) is defined as the product of the number of homogenous consumers (N), diversity correction factor (DCF) and the ADMD. The coincidence factor is defined as k which is determined empirically based on a set of homogenous set of consumers. The number of consumers where the ADMD flattens out differs from literature with Bary in the 1930's citing 30, 50 to 100 customers, Gaunt et al. (1999) consider the number to be approximately 150 consumers, Eskom together with Council for Scientific and Industrial Research (CSIR) states 1 000 customers and Boggis refer to a very large group of consumers (that is, close to infinity) (Bary, 1945:625; CSIR, 2000; Eskom, 2000).

It is noted that this empirical method is still being used – there has been work performed by Herman et al., which indicate that the introduction of the diversity factor either inflates or deflates the ADMD resulting in an error in calculation of the residential load for cases in which the number of consumers is below 30 (Gaunt *et al.*, 1999). The deterministic approach is based on empirical formulae which is limited due to the probabilistic, time dependency and unpredictable nature of electrical loads which is not entirely built into the empirical formulae.

1.3.1.2 Load Requirement – Probabilistic Approach

Electrical load measurements reflect dependency on additional parameters which need to be incorporated into the calculations of the residential load. These factors were highlighted by Bary in his paper from readings and measurements which were performed over a period of a decade between the 1930's to the 1940's (Bary, 1945:625).

These factors consist of human elements and natural elements which are of a statistical nature – these factors are namely: population habits, climatic conditions, social behaviour and control of service methods. It must be noted that the only route to obtain accurate results based on these factors can only be accomplished through actual measurements and mathematical modelling done to predict the outcome with a reasonable degree of error. A data collection project was initiated in South Africa in 1988 with the objective of modelling residential load (Herman & Gaunt, 1991). The data revealed that in the residential customer load profile there are other factors which have a significant impact on the modelling of the residential load.

These factors were listed by Gaunt and Herman as income, number of occupants in the dwelling and community habits (it is worth noting that the community habits were part of Bary's important factors as well). Due to the named factors above, an empirical approach for residential load modelling was deemed not highly accurate for a homogenous group with 30 consumers or less.

There were numerous attempts to best represent the residential load ranging from Gaussian to the normal probability density functions. Herman was able to provide the most approximate residential load model though a modified Beta probability density function (Herman & Kritzing, 1993:46). This introduces three parameters which address the skewness, shape and the scaling of the Beta probability density function. South Africa has adopted this as the mean in order to justify the cost for electrification projects as residential load estimation is critical in electrification design.

The probabilistic approach is based on South African residential consumer load data collected by the South African Bureau of Standards (SABS) for a period of over two decades. The approach uses residential consumer load data to determine the appropriate design parameters to be implemented in electrification design. In the instances where consumer load data is available, the Alpha (α) and Beta (β) parameters can be determined. These Beta probability density function ($p(x)$) parameters are determined using the circuit breaker size (c), the mean (μ) and standard deviation (σ) of the collected consumer load data. The Beta probability density function and associated parameters are provided by the formulae below as follows:

$$p(x) = \frac{x^{\alpha-1}(1-x)^{\beta-1}}{\int_0^1 x^{\alpha-1}(1-x)^{\beta-1}dx} \quad \dots (4)$$

$$\alpha = \frac{\mu(c\mu - \mu^2 - \sigma^2)}{c\sigma^2} \quad \dots (5)$$

$$\beta = \frac{(c - \mu)(c\mu - \mu^2 - \sigma^2)}{c\sigma^2} \quad \dots (6)$$

$$\sigma^2 = c^2 \frac{\alpha\beta}{(c + \beta)^2(\alpha + \beta + 1)} \quad \dots (7)$$

$$\mu = c \frac{\alpha}{\alpha + \beta} \quad \dots (8)$$

The circuit breaker size essentially provides the scaling of the Beta probability density function. If $\alpha < \beta$, this results with the Beta probability density function being left skewed. For the case, $\alpha > \beta$, the Beta probability density function is right skewed. For the scenario in which $\alpha = \beta$, this results in a normal distribution function as there is no skewness. The ADMD in kVA is provided by the product of the mean of the consumer load data and the single phase nominal voltage (230V in South Africa). A left skewed Beta probability density functions means that the load distribution along the low voltage (LV) feeder is more likely to have consumers drawing low current whereas for a right skewed function the LV feeder load distribution has consumers drawing high current.

1.3.2 Network Reliability

In power systems, network reliability is predominately focused from the originating sources, which is at the generation and transmission level. In this dissertation reliability shall be defined at the distribution level. By definition, network reliability is the probability of a network performing its design functions adequately within the design conditions for the intended design period. As a network can consists of components, network reliability of the network is thus dependent on the individual components making the network.

Two further factors of great significance to comprehend associated with network reliability are namely, outages and interruptions. An outage is the failure of part of the power distribution system while an interruption is the failure to supply one or more consumers in the power distribution network. It is evident from the definitions of the factors that outages – which are the cause of service problems, leads to interruptions – which is the result of failure to provide service to consumers (Willis, 2004a:115).

Network reliability consists of primarily three aspects, namely – frequency, duration and severity. The frequency refers to how often the specific occurrence occurs; the duration refers to how long the specific occurrence lasts' for and severity is the extent as well as the impact on the consumers.

The frequency aspect is associated with the type and condition of network, with the duration aspect, more aligned with the management of fault once it has occurred (Eskom, 2015). During the design stage, an aspect in which control can be freely exercised is the resultant severity on the consumers due to the distribution network interruptions. The influence on the aspects of frequency and duration of the service interruptions are more on the operations and maintenance stage.

As a means to be able to measure and set objectives for reliability, reliability indices are used within the power distribution industry. There are various indices which seek to measure frequency, duration and severity to consumers. There are interesting areas of research within reliability which seeks to formulate an index which relates frequency and duration. Though outside the scope of this dissertation, the quest is finding a balance between frequency and duration, which weighs more and their relation as different consumers' have different perspectives on the importance of one aspect over the other.

The reliability indices which are of significance in this dissertation shall be the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI) and the Customer Average Interruption Duration Index (CAIDI). These indices primarily contribute in the identification of the shortcomings and strengths of the distribution networks. The duration indices are key as the longer the duration, either the consumer or even worse the system is interrupted resulting in a major loss in revenue. The duration of the interruptions can be used to determine which network topologies are more prone to longer interruption durations.

The frequency index is as important as the network topologies which have more interruptions can be easily identified. Networks which tend to have frequent interruptions will also result in loss of revenue. These networks can be identified through the analysis of the SAIFI. The most significant impact shall be the cross analysis of the duration and frequency indices to determine the severity within the distribution networks in relation to the loss of revenue for the different electrification network design topologies. The combination of the duration and frequency indices shall make it easy to determine the optimal electrification network design topology.

In South Africa, licensed power distributors need to provide their annual figures to National Energy Regulator of South Africa (NERSA) as part of their annual reporting. These three indices are mathematically defined below:

$$CAIDI = \frac{\text{sum of the durations of all customer interruptions}}{\text{number of customer interruptions}} \quad \dots (9)$$

$$SAIDI = \frac{\text{sum of the durations of all customer interruptions}}{\text{total customers in system}} \quad \dots (10)$$

$$SAIFI = \frac{\text{number of customer interruptions}}{\text{total customers in system}} \quad \dots (11)$$

1.3.3 Financial – Life Cycle Costing

Costing in electrification infrastructure projects, in essence in engineering projects is a critical element which can either make or break a project. Costing is a commodity which has to be traded for the acquisition of services, materials and equipment required in a project. The financial analysis shall be over the life cycle of the project in order to provide logical decisions on a basis of sound financial judgement. The electrification infrastructure project life cycle is depicted in the process flow diagram below:



Figure 1-1: Electrification Project Life Cycle

The bulk of the costs in electrification infrastructure projects are attributed within the first two stages which are the planning-design and construction phases respectively (Bumby *et al.*, 2010:5590; Willis, 2004b:148). In this dissertation, the process for the acquisition of the particular land to be developed shall be assumed to be completed and the only costs associated with land shall be for the acquisition of servitudes for services. In literature, these initial costs are based on various elements which influence the bottom line costs (Economic Regulation Authority, Western Australia, 2011).

The third component in the life cycle of electrification projects is associated with the operations and maintenance costs. In South Africa, this is a significant component in which supply authorities tend to encounter difficulties, under spend and in most cases, tend not to undertake the maintenance of the installed electrical infrastructure (Maphumulo & Fowles, 2008; Van der Merwe, 2008).

The objective of this stage in the life cycle is to ensure that the installed infrastructure performs within its original design parameters with natural wear and tear taken into cognisance. A significant amount of literature has covered the individual components utilised in the electrification infrastructure projects.

This ranges from cables, conductors and transformers (Ariffin, 2015; Mladenovic *et al.*, 2015). Innovative work still continues into research, analysis and optimisation of these components which eventually does have an effect on the overall electrification infrastructure system.

The final stage of the project life cycle – decommissioning, which occurs prior to the electrical infrastructure having reached its design life span which in this dissertation is referred to as 20 years. This stage entails the safe removal of the electrical infrastructure from operations in the electrical network as the design life span has been reached. The entire life cycle costing of the electrification infrastructure is represented by the function below:

$$LCC = C_i + C_{om} + C_d \quad \dots (12)$$

C_i is the initial investment costs which covers the costs associated with the planning-design and construction stages. C_{om} is defined as all the costs associated with the operations-maintenance stage of the infrastructure life cycle. C_d is the costs associated with the decommissioning of the electrical infrastructure once the design life span has been reached.

1.3.4 Social and Environmental

There are several states in the United States of America, European Union countries and Australia which put aside funds to investigate the feasibility of converting existing overhead electrical infrastructure to underground networks. Part of the findings by the commissions elaborated on the social and environmental benefits. The primary driver for the United States of America commissions was to address the issues of aesthetics, network reliability and electrical services availability post natural disasters (Hall, 2012).

In these studies, the issue of undergrounding was more prevalent as a case of reactive approach after the natural disasters. The conclusion in the studies conducted were primarily as follows:

- There is a significant high cost associated with the conversion of the existing overhead infrastructure to underground networks.
- The possible benefits of the conversion exercise based on available and lack of sufficient analysed data, seem to indicate that the probable justifiable benefits, namely savings realised from overhead network operations and maintenance, vehicle accidents onto overhead lines, post natural disaster restoration damage and lost sales during interruptions are not sufficient to offset the high initial costs for the conversion of distribution electrical infrastructure to underground.

- Due to the high costs associated with the entire conversion of distribution networks, some “critical” portions of the distribution networks are financially justifiable to be converted to underground networks.

In the European Union countries and Australian studies, the main drivers were attributed with the improvement of the energy security of the electricity distribution system and the enhancement of the electricity supply standard to consumers by addressing network reliability issues in areas with existing overhead electrical infrastructure (Commission of the European Communities, 2003; Halcrow Pacific (Pty) Ltd in association with Albany Interactive (Pty) Ltd, 2011). The conclusions of the studies which are based on the actual implemented projects by the Western Power supply authority are as follows:

- A substantial benefit realised by property owners’ due to an increase in real estate prices and with the overall return on executed projects yielding a positive nett present value.
- Lower maintenance costs and avoided overhead electrical distribution infrastructure replacement costs.

An interesting component which is outside the scope of this dissertation from all the studies is the funding component for rolling out the proposed undergrounding – with sufficient analysed data based on actual projects, an equitable contribution from the different stakeholders based on the benefit to be achieved seems to be the consensus.

The benefits of aesthetics within an overhead and an underground network environment can be difficult to quantify with the exception of the actual visual difference in the neighbourhoods as well as the real estate appreciation. The study conducted in Australia indicated that part of the social benefits for the conversion to underground electrical infrastructure results in an increase in amenities and desire for tourism (Economic Regulation Authority, Western Australia, 2011). This seeks to address the social well-being and satisfaction of consumers with respect to the different available electrification design topology.

There are effects experienced by the consumers in the event of an unexpected social occurrence, for instance a motor vehicle accident which results in the interruption of the supply of electricity to the consumers. One of the effects is the perceived level of safety associated with the different network design topologies. Motor vehicle accidents tend not to only cause power interruptions but leads to other social inconveniences which are not easily recorded in literature and easily quantified.

Furthermore, the consumers' perceptions towards pedestrian walk ways, opportunities for increased development activity and with regard to the environment perception to tree trimming which results in the diminishing potential habitat for wildlife. Numerous studies have been performed and are continuously done on the effects of magnetic fields and electric fields, collectively referred to as Electromagnetic Fields (EMF) in electricity distribution (Holbert *et al.*, 2009:1618). There are set regulatory limits which regulate the distribution network design for compliance purposes.

1.3.5 Analytical Hierarchy Process

AHP is a multi-criteria decision-making method developed in the 1970's by mathematician Thomas Saaty which applies paired comparisons on a set of defined criteria expressed in matrix form (Saaty, 1987:168). Decomposition of problems into hierarchies is formed on the basis of the judgements of decision makers in order to make an informed decision. Essentially the AHP is a decision tool which analyses, ranks, prioritises and evaluates decision alternatives. The concept of the approach is to prohibit committing to ad-hoc and unstructured decisions which ultimately results in poor and unjust decision outcomes.

The formulation of the hierarchy is decomposed into the primary objective which is the goal being analysed – a set of criteria are then used in order to determine the goal – alternatives which satisfy the goal are compared. The hierarchy is similar to an inverted tree with the goal being analogous to the root and the alternatives being the leaf nodes (Bhushan & Rai, 2004). This is represented in the figure below:



Figure 1-2: Generic Hierarchic Structure of the Analytical Hierarchy Process

On the basis of the hierarchic structure pair-wise comparison of firstly the criteria is analysed to form a matrix and following that an analysis of each criterion against the available alternatives are also computed. The relative importance of each criterion being compared is provided by the calculation of the eigen-vector of the comparison matrix. Due to the subjective nature of the AHP, a sensitivity analysis on each comparison matrix is performed in order to ensure that the comparisons are consistent with no contradictory data – provision for a degree of tolerance is provided in literature (Saaty, 2008:91). The product of the rating of the alternative and the weight of the criteria is aggregated to obtain the global rating. In AHP a common criterion is used to produce weight values for each alternative based on judgement importance of one alternative over another.

The pair-wise comparison applies the following scale in forming the comparison matrix.

Level of Importance	Definition	Explanation
1	Equal importance	Equal Contribution to the Objective
2	Weak or Slight	
3	Moderate Importance	Experience and Judgement Slightly Favour One Activity Over Another
4	Moderate Plus	
5	Strong Importance	Experience and Judgement Strongly Favour One Activity Over Another
6	Strong Plus	
7	Very Strong / Demonstrated Importance	An Activity is Favoured Very Strong Over Another; Its Dominance Demonstrated in Practice
8	Very, Very Strong	
9	Extreme Importance	An Activity Favouring the Highest Order of Affirmation

Table 1-1: Fundamental Scale for Pair-Wise Comparisons Using Absolute Numbers

The major issue with the field of engineering is the high risk associated with the profession – engineering decisions do not only affect the individual, but the general public is affected. Hence a major part of risk mitigation involves proper planning and taking sound engineering decisions (Parihar & Bhar, 2015:77). It is of utmost importance that logical and sustainable decisions are taken at all times. It is evident from literature that in power system, AHP been implemented in the specific fields of design criteria selection, substations, maintenance and condition monitoring (Chitpong, 2016; Tanaka *et al.*, 2010:3020; Tee *et al.*, 2010:114).

1.4 RESEARCH OBJECTIVES

The objective of the research dissertation is to present an evaluation model which determines which electrification topology needs to be implemented in residential developments. First and foremost, the electrical technical requirements for the development shall need to be fulfilled.

This is defined in the consumer load classification for the specific type of development (CSIR, 2000; SANS, 2007). On fulfilment of the consumer load classification requirement, different available options in terms of the electrification design topologies shall be investigated. The technical constraints and benefits for each option shall be presented. The economic considerations shall be introduced in order to form a business case for each option. The social factors shall be taken into account in the model and the end result shall seek to establish a reasonable balance for these governing factors. The primary factors in the model shall be the technical requirements.

This shall aid electrical supply authorities and developers in deciding the appropriate electrification design topology implemented for residential developments. The developer and / or electrical supply authority knowing the consumer load classification for the proposed residential development, shall be in a position to input the information and obtain a decision on the design topology to be implemented.

This shall be on the basis of the fulfilment of the electrical load requirement and establishing a balance between the technical details, economic considerations and social influences and/or factors. These different factors shall have the principles of sustainability embedded within, therefore ensuring the end product shall be a decision taken on the basis of sustainable principles. The definition of sustainability originates from the United Nations and is defined as the systematic approach to meet the current needs without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987).

1.5 SCOPE OF RESEARCH

The scope of the model shall be primarily focused on the planning-design and construction phases of the infrastructure life cycle. The detailed operations-maintenance and decommissioning phases of the infrastructure life cycle shall be incorporated into the evaluation model even though there is limited existing data analysed on these phases in the infrastructure life cycle. In this dissertation this shall be assumed to be a period of 20 years to 30 years.

The decision shall be on the basis of fulfilment of the electrical requirements for the given consumer load classification. The boundaries for the factors applied in the model shall commence from the consumer point of supply at the specific erf, LV reticulation and terminate at the medium voltage (MV) distribution within the development. This shall be inclusive of the assumption that bulk supply services to the development are readily available at the development boundary.

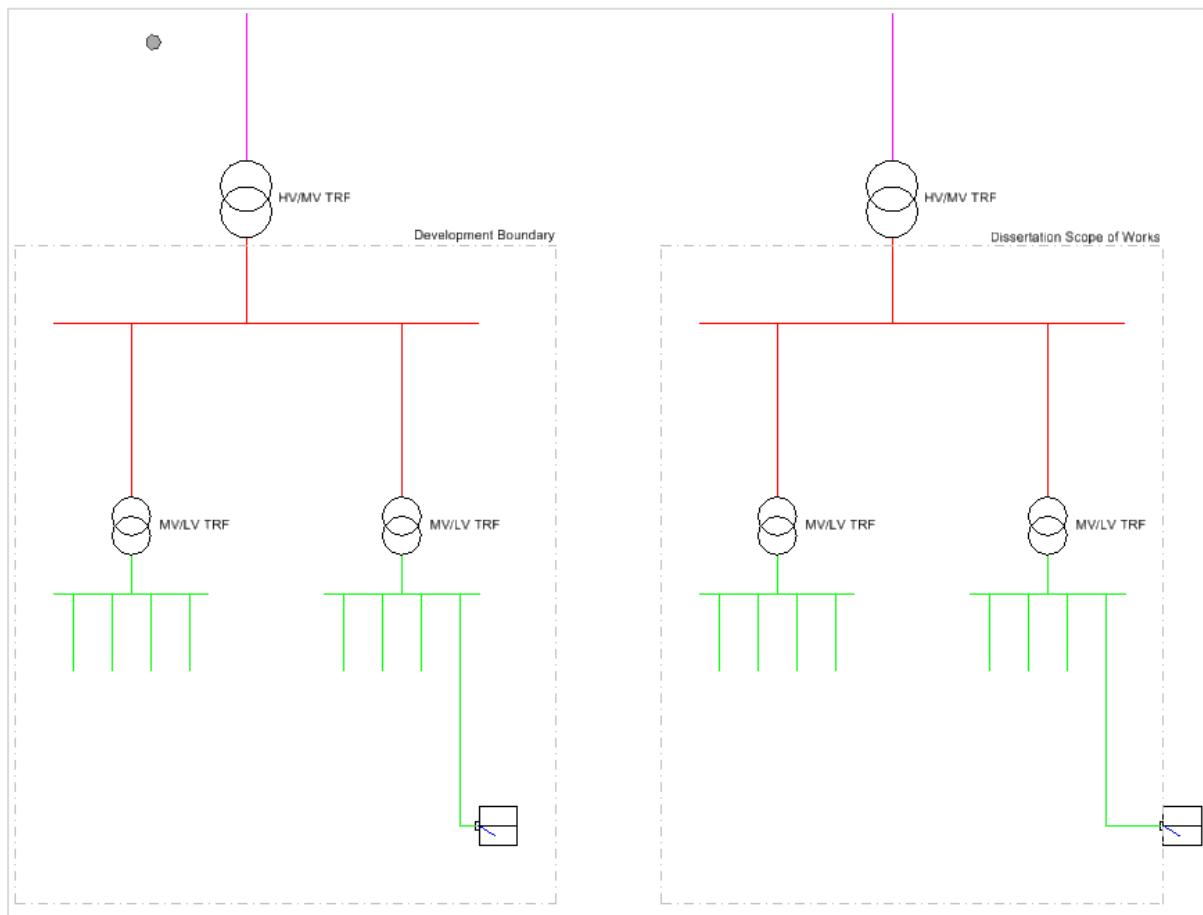


Figure 1-3: Scope of Research Boundary for the Evaluation Model

1.6 METHODOLOGY OVERVIEW

The methodology to be implemented in the evaluation model shall be the globally accepted design technique, that is, functional decomposition which is characterised by simplicity, flexibility and intuition. In functional decomposition the overall system functionality consists of subsystems which are iteratively determined and have their own functionality which are essentially the fundamental building blocks of the overall system (Ford & Coulston, 2008a; Ford & Coulston, 2008b).

The methodology shall be a combination of the bottom-up and top-down approaches in order to maximise overall system effectiveness. A detailed analysis of the inputs to the systems shall be performed – since the inputs to the system shall be outputs of subsystems building up the overall system. This is essential as the output integrity is as good as the integrity of the input, hence the overall system performance.

Furthermore, the concept of AHP shall be incorporated into the evaluation model. As a decision-making method, AHP applies paired comparisons on a set of defined criteria expressed in matrix form. The comparison judgement shall be an input based on the user requirements on the basis of the defined criteria. This shall result in the derivation of ratio-scaled weights and rankings for the respective available design alternatives. A design and development phase shall follow, in which the sub-systems and the entire evaluation model is designed and developed. The final phase shall be the testing of the evaluation model on a case study with appropriate recommendations and conclusions made.

1.7 RESEARCH OUTCOMES AND DELIVERABLES

Residential development electrification is one of the core components required in the development of societies. In all developing countries, South Africa and largely the rest of the African continent, it is of utmost importance that the development of these countries is done in a sustainable manner not only for the current generation but for the future generations as well. With that context in the background the research outcomes and deliverables of this dissertation are set out as follows:

- A review and lessons learnt of how developed countries approach residential development electrification.
- An in-depth investigation and analysis of the different electrification design topologies.
- A Microsoft Excel based network design topology evaluation model with the objective of aiding the supply authority or developer in taking an informed and sustainable decision on the network design topology to be implemented.

Upon the successful completion of the compilation of the above, it is reasonable that there shall be a tool which can be utilised to substantiate sustainable residential electrification. This will result in a benefit to the built environment industry and a further additional contribution to the existing body of knowledge.

1.8 VERIFICATION AND VALIDATION OF EVALUATION MODEL

The model data shall be verified to ensure that the input and the projected data is correct. This shall be achieved by implementing and comparing the model data with existing supply authorities design requirements. For validation purposes a case study shall be carried out on the network design topology evaluation model and results of the model compared to those of an educational / commercial multi-criteria decision-making software package – Super Decisions.

1.9 OVERVIEW OF DOCUMENT

This first chapter provides an overview of the problem and presents context for the objective of the dissertation. In **Chapter 2**, a thorough literature review on the fundamentals of the factors which are to be used in the evaluation model are investigated. This shall seek to lay the foundation for the basis of the development of the model. In **Chapter 3**, a detailed investigation and analysis of the different electrification options is undertaken.

The findings and principles presented in the previous chapters shall make it possible for the presentation of the evaluation model in **Chapter 4**, taking into cognisance the different sub-systems. In **Chapter 5**, the developed evaluation model shall be validated, implemented into a case study and the results be presented. In **Chapter 6**, the conclusion and recommendations of the model shall be thoroughly discussed.

CHAPTER 2

2. LITERATURE SURVEY

2.1 OVERVIEW

The research background in Chapter 1 of this dissertation provided a perspective mainly from developed countries on the conversion of existing overhead electrical infrastructure to underground electrical networks. In this chapter, the planning and design perspective component is presented in order to have an all-inclusive picture for sustainable residential electrification.

An in-depth survey of the documented literature will be carried out which guides the electrification design planning within the borders of South Africa and thereafter a review of the methods applied by developed nations. For the case within our borders, the National Standards, National Rationalised Specifications, Human Settlement Planning Guidelines, Eskom Standards and other supply authorities' standards shall be analysed. For developed nations namely, Australia, the United Kingdom and the United States of America, the policies together with the standards of the supply authorities shall be analysed.

The process of electrification design-planning consists of different interaction with different stakeholders and authorities. The graphical representation below provides a high-level process flow for electrification design planning with the following assumptions:

- Town planning provisions are approved.
- Bulk supply capacity on the medium voltage level is available.
- Funding is available.
- All other statutory requirements are approved, that is, environmental impact assessments, as well as health and safety requirements amongst others.

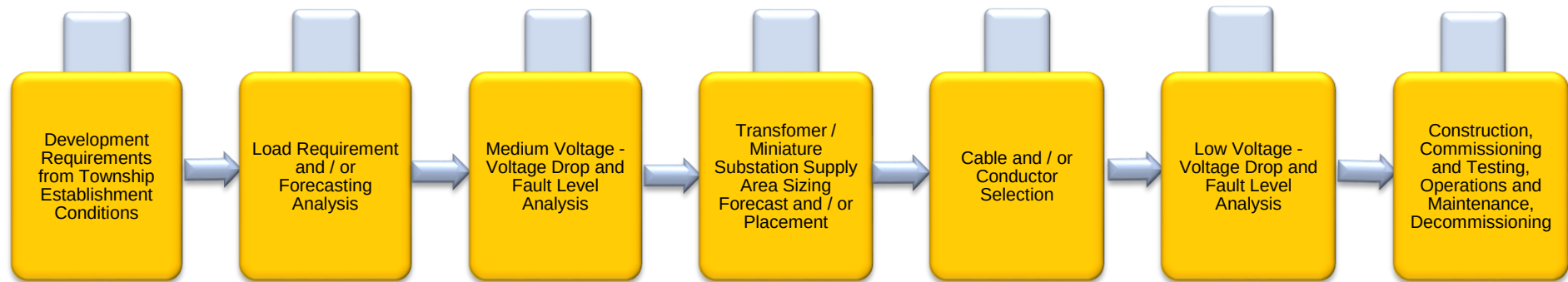


Figure 2-1: Electrification Design Planning Process Flow Life Cycle

In the process of design planning, the best practice exercise of design review is applied in each milestone of the design planning process in order to ensure compliance with the statutory design standards and regulations. As indicated in the previous chapter, the challenge in residential electrification design is with the LV feeder design, hence Eskom and most supply authorities use commercial software packages to confirm conformance with LV voltage drop limits as guided by the voltage apportionment limits in the quality of supply rationalised user specification National Rationalised Specification (NRS) 048 Electricity Supply – Quality of Supply (NRS, 2007).

2.2 SOUTH AFRICAN DESIGN PLANNING

The electrical distribution design planning in South Africa is guided by the South African National Standards (SANS), Human Settlements Planning Guidelines, Eskom Standards and specific supply authorities (mainly established metropolitan municipalities) standards. The documented design planning shall focus on residential electrical distribution network planning.

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2.3.1 South African National Standards – SANS 507 / NRS 034

The SANS 507 is the fundamental document which sets out the provisions for the planning of electrical distribution networks in residential areas (SANS, 2007). The standard provides the requirements in the planning of residential electrification. This incorporates network design factors, planning procedures for the entire network including distribution network earthing, metering, protection, LV distributor requirements, load modelling and financial analysis.

This is the Holy Grail document which guides the planning and design of residential electrification projects in the country. In the standard, in terms of the determination of the load requirement, the standard refers to the statistical approach. The statistical load estimation model, which uses statistical parameters namely, α and β parameters with a scaling factor C, briefly described in Chapter 1 of this dissertation is thoroughly presented in the standard. In the standard, in terms of reliability, a cross reference is made to the NRS 048 – Quality of Supply – Part 2 which deals specifically with the network reliability requirements in detail. This includes the voltage drop limitations, regulation and reliability.

The financial analysis is provided on a high-level basis in which the concept of Nett Present Value is presented in order to determine a beneficial investment decision. The social aspects, are to an extent, incorporated into the load estimation model, in which the consumer class is defined and this relates to the income of the particular consumer load classification. The environmental aspects are addressed in the planning procedures whereas the issue of aesthetics is not explicitly defined in the standard.

The standard addresses the LV distribution technology used in the electrification of residential developments, namely either a three phase, dual phase or single-phase system – network design topology in terms of either overhead or underground networks is not explicitly defined in the standard as reference is made to both cables (underground networks) and conductors (overhead networks). The decision on the network design topology is left to the discretion of the designer or the requirements of the developer and / or supply authority.

In the standard the following consumer classification incorporating the Living Standard Measure (LSM) is provided which indicates the design parameters.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Current type			Load parameters – 7 years ^{c def}						Load parameters – 15 years ^{c def}					
Consumer class	AMPS ^a and LSM ^a class	Income range ^b (gross R/month)	a	b	c	ADMD kVA	μ A	σ A	a	b	c	ADMD kVA	μ A	σ A
Rural settlement	LSM 1 (low end)	0 to 600	0,30	2,98	20	0,42	1,83	2,78	0,35	2,88	20	0,50	2,17	3,03
Rural village	LSM 1 and 2	400 to 900	0,43	2,52	20	0,67	2,91	3,55	0,48	2,13	20	0,84	3,65	4,07
Informal settlement	LSM 3 and 4	800 to 1 500	0,77	9,88	60	1,00	4,35	4,56	0,91	8,80	60	1,30	5,56	5,36
Township area	LSM 5 and 6	1 500 to 3 000	1,05	7,81	60	1,64	7,13	6,18	1,22	5,86	60	2,37	10,30	7,96
Urban residential I	LSM 7	3 000 to 5 500	1,23	5,56	60	2,50	10,87	8,28	1,25	3,55	60	3,59	15,61	10,93
Urban residential II	LSM 7 and 8	5 500 to 8 500	1,45	6,07	80	3,54	15,39	10,81	1,42	4,10	80	4,72	20,52	13,68
Urban township complex	LSM 8	8 500 to 12 000	1,45	5,75	80	3,70	16,09	11,20	1,42	4,13	80	4,70	20,43	13,63
Urban multi-storey/estate ^f	LSM 8 (high end)	12 000 to 24 000	1,43	4,41	80	4,50	19,57	13,15	1,37	3,39	80	5,30	23,04	15,09

^a Living standards measure (LSM) as quoted in the All Media and Product Survey (AMPS) conducted annually by the South African Advertising Research Foundation.

^b Average household income ranges shown for comparative purposes are in 2005 Rands. Any income data collected at a later date should be deflated by the CPI to allow a direct comparison.

^c If the target community matches the description, but the chosen value of *c* is different, new *a* and *b* values can be calculated for the chosen value of *c*, using the formula given in B.4.3.

^d Parameters have been normalized to the climate in the interior of South Africa where the winters are generally cold and with low rainfall. In regions where the winter is cold and wet (e.g. Cape Peninsula), the ADMD is about 12 % higher than that given. In climates similar to that of the Durban coastal region, the ADMD is about 12 % lower than that given.

^e Except as indicated in *f* below, the parameters have been derived from carefully monitored case studies around the country, and reflect best knowledge at the time of publication of actual consumer demand over time. The actual load parameters used depend upon the strategy of the planner with regard to phasing of capital expenditure.

^f Parameters for this consumer class have been extrapolated from existing data, since no sample load data have yet been collected from such consumers. Loads significantly higher than the ADMD shown in LSM 8 (high end) can be expected in the case of specific high-consumption developments. In such cases, estimated load data should be obtained from the relevant local authority or licensee.

Table 2-1: Domestic Consumer Classification (SANS, 2007)

LSM is a market segmentation framework developed by the South African Audience Research Foundation (SAARF) (SAARF, 2017). The LSM basically measures and classifies different households scores based on the contents / appliances within the specific household.

The most recent LSM scale ranges from 1 to 10, with ranges 7 to 10 incorporating sub-ranges low and high. This results in LSM effectively having a total of 14 discrete ranges. It is part of the reasoning that this research dissertation is compiled in order to provide an evaluation model for the different available network design topology options. Yes, the standard is there to provide the statutory requirements and the model seeks to supplement the standard requirements by providing a logical basis for the implementation of the network design topology.

2.3.2 Guidelines for Human Settlements Planning and Design – Red Book

This is a thorough guideline which was published in the early 2000's and provides planning guidelines for engineering services with regard to the design planning of residential developments (CSIR, 2000). The book covers different disciplines and the electrical engineering requirements / guidelines are presented in Chapter 12 of the book. The concept of a phased approach is introduced in the guidelines – this is guided by an overall master plan for the development. The guidelines were compiled on the basis of the electrification standards which were applicable at the time namely, the NRS 034-1:1997 (later SANS 507 from the 2007 publication).

In terms of load forecasting, three ADMD estimation models are presented namely, appliance modelling, direct measurement and energy load factor. Appliance load modelling is based on the contribution of different appliances during the peak period for a homogenous group of consumers. The direct measurement method consists of measuring a residential area maximum demand for a specific period during a peak demand calendar month (normally during the coldest months, namely May, June and / or July) in residential areas in which load saturation has been reached.

The direct measurement method yields accurate results in which the measurements are taken in areas whereby these specific areas have been electrified for a period of not less than 15 years. The energy load factor method requires a detailed history of energy sales in a residential area and the availability of the load factor in the particular residential area to provide reliable results. Otherwise, an estimation of the load factor together with the forecasted energy sales can be used to determine the ADMD. The guidelines adopted the consumer classification of the NRS 034-1 with the addition of the relation between the domestic density classifications to the load density.

DOMESTIC DENSITY CLASSIFICATION	STAND SIZE (m ²)	AVERAGE LOAD DENSITY (kW/km ²)
URBAN:		(ADMD min = 0,5 kVA ADMD max = 4,5 kVA)
High density (HD)	<1 000	500 to 30 000
Medium density (MD)	1 000 to 4 000	300 to 5 000
Low density (LD)	4 000 to 20 000	100 to 1 500
RURAL:	>20 000	0,5 to 250

Table 2-2: Domestic Density Classification (Eskom, 2012)

The guidelines put emphasis on optimisation of designs with a long-term vision – thus promoting the elements of sustainability in the designs. The planning procedures, low voltage feeder design and analysis are adopted from the NRS 034.

2.3.3 Eskom – Standards

Eskom holds the license for the majority of the distribution networks in the country and supplies more than a third of the continent's electrical power requirement (Eskom, 2017). It is the major custodian within the electricity industry and has over years developed solid design standards which are implemented not only by Eskom but by other supply authorities. In terms of residential electrification design and planning, there are several detailed Eskom standards which are applicable.

In the document, Distribution Network Planning Standard – 240-75757028 (Eskom, 2014), all the requirements for distribution network planning within the Eskom networks are detailed. The time lines for Eskom catered for network planning is defined as a period of 20 years for master plans and development plans have a period of 10 years with reviews at 3-year intervals. In terms of residential load forecasting the standard makes provision for different consumer load classifications. The consumer load classification caters for different residential developments from low income groups to the upmarket luxury groups. These classifications are provided in the table below.

Classification	ADMD per stand
Domestic Electrification	0.2kVA < ADMD < 1.0kVA
Domestic Low Income	1.0kVA < ADMD < 3.0kVA
Domestic Normal	3.0kVA < ADMD < 6.0kVA
Domestic Up Market	6.0kVA < ADMD < 8.0kVA
Domestic Luxury	ADMD > 8.0kVA

Table 2-3: Eskom Consumer Classification ADMD Table (Eskom, 2012)

Geo-based load forecasting is a type of spatial load forecasting which uses the geographical area to predict the load requirement. The Eskom standard is primarily based on the work of H.L. Willis, on the basis of the detailed book titled Spatial Electric Load Forecasting (Willis, 2007). Geo-Based load forecasting has three methods namely; trending method, simulation method and hybrid method which is a combination of the first two named methods. In the trending method, historical peak load data is collected and extrapolated into a polynomial function to provide a forecast of future load. Substantial literature has been recorded on the method and improvement techniques on the computation of the polynomial function (Heunis, 2013:3; Willis & Northcote-Green, 1983:243).

The simulation method is considered to be more accurate than the trending method when properly applied as it allows for multi scenario planning. In this method, a model is created which seeks to provide an estimate of the load forecast by considering the when (period), where (location) and how (the drivers of the load). This incorporates the phenomenon of load growth – load growth occurs due to two events, namely:

- increase in consumer numbers.
- increase in consumption by consumers.

Eskom has adopted the geo-based load forecasting model for the load forecasting of their transmission and distribution networks. As residential areas fall within the distribution network, residential load estimation forms part of geo-based load forecasting through consumer classification. This method is extensively presented in the Eskom document, Geo-Based Load Forecast Standard 34-1284 (Eskom, 2012). The methodology caters for long term load forecasting for a period of 20 years which is critical as it mitigates the risks of unnecessary unplanned load which was not catered for.

In the standard, Eskom provides load sub-class models for residential areas based on data collected over a period of time in Eskom supply areas.

The source for the load profile and load modelling is the NRS 034 Load Research Project up to the year 2009. The modelled sub-class consists of parameters which makes it possible to forecast future loading and behaviour based on collected historical data. The syntax of the sub-classes is indicated in the figure below:

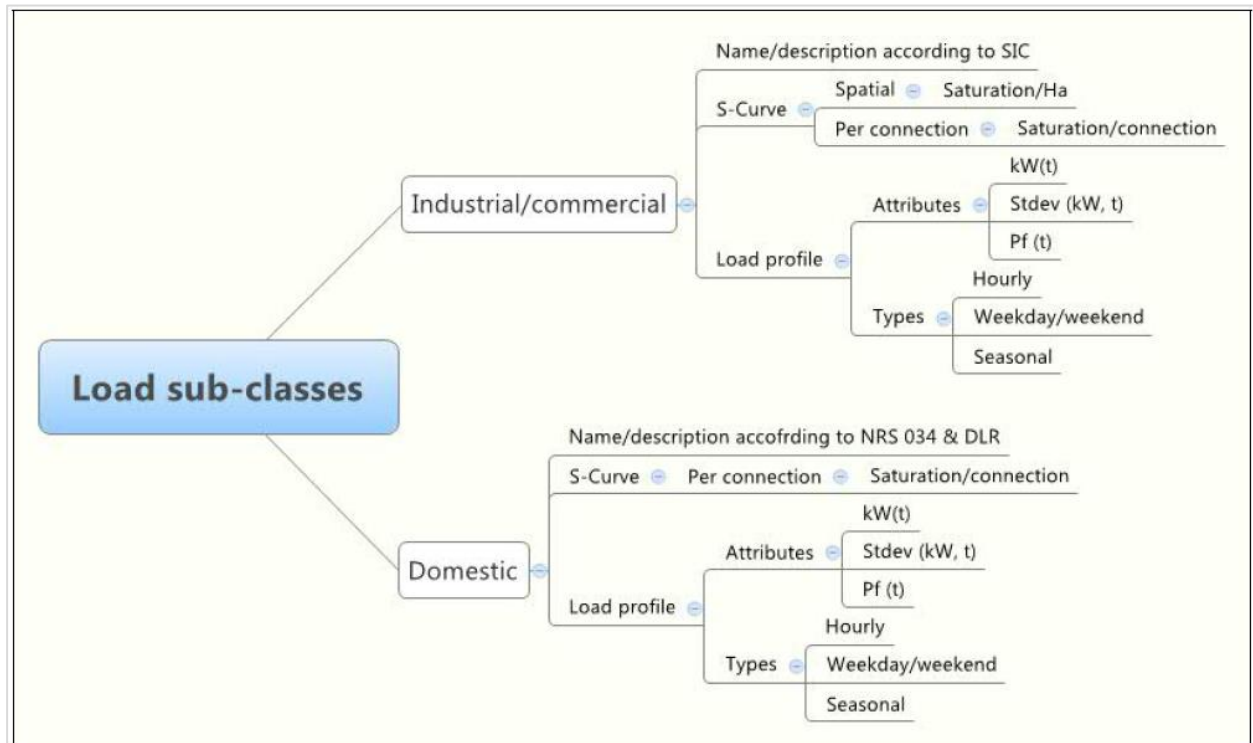


Figure 2-2: Eskom Load Sub-Classes Definition (Eskom, 2012)

In an attempt for alignment, Eskom has linked the domestic load sub-classes with the consumer classification as defined in the LSM. LSM essentially measures household wealth and is reviewed on an ongoing basis. In their data collection, Eskom provides the following domestic load classification in terms of forecasted maximum demand, energy consumption and load growth.

Serial	Subclass name	Saturation value ¹² [kW/connection]	Saturation value ¹³ [kWh/mth]	Load growth curve-shape	Notes
1	Rural scattered LSM 1-2	0.41	113.00	Sigmoid	Derived from a lookup DT PET 2010, Income R1,000/mth
2	Rural village LSM 3-4	0.41	113.00	Sigmoid	Derived from a lookup DT PET 2010, Income R1,000/mth
3	Informal settlement LSM 3-4	0.67	211.00	Sigmoid	Derived from a lookup DT PET 2010, Income R2,000/mth
4	Township LSM 5-6	1.69	470.00	Sigmoid	Derived from a lookup DT PET 2010, Income R5,500/mth
5	Urban res 1 LSM 7i-7h	2.28	668.00	Sigmoid	Derived from a Lookup DT PET 2010, Income R10,000/mth
6	Urban res 2 LSM 8i-9i	2.88	864.00	Sigmoid	Derived from a lookup DT PET 2010, Income R18,000/mth
7	Urban townhouse 1 LSM 7i-8h	2.62	785.00	Sigmoid	Derived from a lookup DT PET 2010, Income R15,500/mth
8	Urban Townhouse 2 LSM 9i-10h	4.82	1480.00	Sigmoid	Extrapolate DT PET 2010, Income R46,000 to estimate kWh. Use ULM control profile ¹⁴ in this band (2010 data).
9	Urban Estate LSM 10h+	8.11	2550.00	Sigmoid	Extrapolate from DT PET2010, to income R100,000/mth to estimate kWh. Use ULM control profile in this band (2010 data).
10	High- rise (small) LSM 5-6(i.e. Flats), LSM 5-6	1.54	439.00	Flat line	Derived from a lookup DT PET2010, Income R5000/mth. 60-80M ² floor area. Main impact is income-related, expressed per flat.
11	High-rise (medium) LSM 7i-8h (i.e. Flats), LSM	2.10	558.00	Flat line	Estimated from DT PET DT PET2010, with Income R7000/mth. Floor area 100M ² . Expressed per flat.
12	Hostel LSM 4-6	1.10	337.00	Flat line	Derived from a lookup DT PET2010, Income I= 3500/mth. Assumes dwelling units are shared.

¹² Estimated demand at year 15

¹³ Estimated consumption at year 15

¹⁴ ULM customers, Fourways: 2010.

Table 2-4: Eskom Sub-Class Classification ADMD Table (Eskom, 2012)

A pretty useful table is also provided which gives the household density at saturation for the different housing types.

Housing type	Dwelling density	Stand size m ²	HH per Ha
Informal housing	HD	122	82
	MD	220	45
	LD	369	27
Formal housing	HD	315	32
	MD	570	18
	LD	1661	6
	ULD	10000	1
Cluster	HD	275	36
	MD	503	20
	LD	750	13
High rise	HD	89	112
	MD	184	54
	LD	404	25

Table 2-5: Eskom Housing Type Dwelling Density at Saturation (Eskom, 2012)

For medium to long term load forecasting, Eskom applies the Gompertz curve in their load growth forecasting applications. The Gompertz curve approximation, which provides the per unitised annual peak load estimate for year n, is described in the formula below:

$$f = \frac{1}{(1 + 10 \times C)} \times \left[(2 + 10 \times C) \times \left(A + \frac{(1 - A)}{(1 + 10 \times C \times e^{\frac{-7n}{B}})} \right) - 1 \right] \quad \dots (1) \text{ (Eskom, 2012)}$$

- A – Starting point of the S curve (for existing loads, this would be the fraction of the saturation load).
- B – Number of years until saturation.
- C – Number between 1 and 10, this varies with the initial growth pattern, 1 translates to strong initial growth and 10 depicts slow initial growth.

The table below provides the load growth curve sensitivity in which load parameters and the rate of growth or the growth pattern are indicated for different saturation years. The table represents different scenarios of growth rates (slow, moderate and high growth), saturation years from 5 to 20 years and different existing load as a percentage of the saturation load of 50%, 20% and 0% respectively.

The column grouping a to c represent the scenario with slow growth, 5-year period to reach saturation load and three scenarios for the existing load as a percentage of the full load (50%, 20% and 0%) over a period of 20 years. The moderate growth column grouping is represented in columns d to f with a 10-year period to reach saturation load and three scenarios for the existing load as a percentage of the full load (50%, 20% and 0%) over a period of 20 years. Two column groupings for high growth are represented in columns g to i and columns j to l respectively with a 15-year and 20-year period to reach saturation load. In these two column groupings the three scenarios for the existing load as a percentage of the full load (50%, 20% and 0%) over a period of 20 years are still applicable.

Description	Percentage of Existing Load to Saturation Load (50%, 20%, 0%), 5 Years to Reach Saturation Load, Slow Load Growth			Percentage of Existing Load to Saturation Load (50%, 20%, 0%), 10 Years to Reach Saturation Load, Moderate Load Growth			Percentage of Existing Load to Saturation Load (50%, 20%, 0%), 15 Years to Reach Saturation Load, High Load Growth			Percentage of Existing Load to Saturation Load (50%, 20%, 0%), 20 Years to Reach Saturation Load, High Load Growth		
	a	b	c	d	e	f	g	h	i	j	k	l
A	0.5	0.2	0	0.5	0.2	0	0.5	0.2	0	0.5	0.2	0
B	5	5	5	10	10	10	15	15	15	20	20	20
C	1	1	1	5	5	5	10	10	10	10	10	10
Years	a	b	c	d	e	f	g	h	i	j	k	l
0	0.5041	0.2066	0.0083	0.5002	0.2003	0.0004	0.5000	0.2001	0.0001	0.5000	0.2001	0.0001
1	0.6119	0.3791	0.2238	0.5099	0.2159	0.0199	0.5030	0.2048	0.0060	0.5021	0.2034	0.0042
2	0.7937	0.6700	0.5875	0.5284	0.2455	0.0569	0.5076	0.2121	0.0151	0.5050	0.2080	0.0100
3	0.9289	0.8862	0.8577	0.5618	0.2988	0.1235	0.5147	0.2236	0.0295	0.5091	0.2145	0.0182
4	0.9805	0.9689	0.9611	0.6164	0.3862	0.2327	0.5257	0.2412	0.0514	0.5147	0.2236	0.0295
5	0.9951	0.9921	0.9901	0.6933	0.5093	0.3866	0.5423	0.2676	0.0845	0.5225	0.2360	0.0451
6	0.9988	0.9980	0.9976	0.7815	0.6505	0.5631	0.5664	0.3062	0.1327	0.5332	0.2531	0.0663
7	0.9997	0.9995	0.9994	0.8617	0.7787	0.7234	0.6000	0.3599	0.1999	0.5475	0.2760	0.0950
8	0.9999	0.9999	0.9999	0.9204	0.8727	0.8409	0.6439	0.4303	0.2879	0.5664	0.3062	0.1327
9	1.0000	1.0000	1.0000	0.9571	0.9314	0.9143	0.6971	0.5153	0.3941	0.5906	0.3449	0.1812
10	1.0000	1.0000	1.0000	0.9778	0.9644	0.9555	0.7553	0.6085	0.5106	0.6207	0.3931	0.2413
11	1.0000	1.0000	1.0000	0.9887	0.9819	0.9774	0.8127	0.7003	0.6254	0.6565	0.4504	0.3130
12	1.0000	1.0000	1.0000	0.9943	0.9909	0.9887	0.8637	0.7819	0.7274	0.6971	0.5153	0.3941
13	1.0000	1.0000	1.0000	0.9972	0.9955	0.9943	0.9049	0.8479	0.8099	0.7406	0.5849	0.4811
14	1.0000	1.0000	1.0000	0.9986	0.9977	0.9972	0.9359	0.8974	0.8718	0.7845	0.6552	0.5690
15	1.0000	1.0000	1.0000	0.9993	0.9989	0.9986	0.9578	0.9325	0.9156	0.8262	0.7219	0.6524
16	1.0000	1.0000	1.0000	0.9997	0.9994	0.9993	0.9727	0.9563	0.9454	0.8637	0.7819	0.7274
17	1.0000	1.0000	1.0000	0.9998	0.9997	0.9997	0.9825	0.9720	0.9650	0.8956	0.8330	0.7912
18	1.0000	1.0000	1.0000	0.9999	0.9999	0.9998	0.9889	0.9822	0.9778	0.9217	0.8747	0.8433
19	1.0000	1.0000	1.0000	1.0000	0.9999	0.9999	0.9930	0.9888	0.9860	0.9421	0.9074	0.8843
20	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9956	0.9929	0.9911	0.9578	0.9325	0.9156

Table 2-6: Gompertz Load Growth Sensitivity Table

The load growth sensitivity for the various scenarios of existing load as a percentage of the saturation load, number of years to reach saturation load and the load growth rate are represented graphically in the figure below.

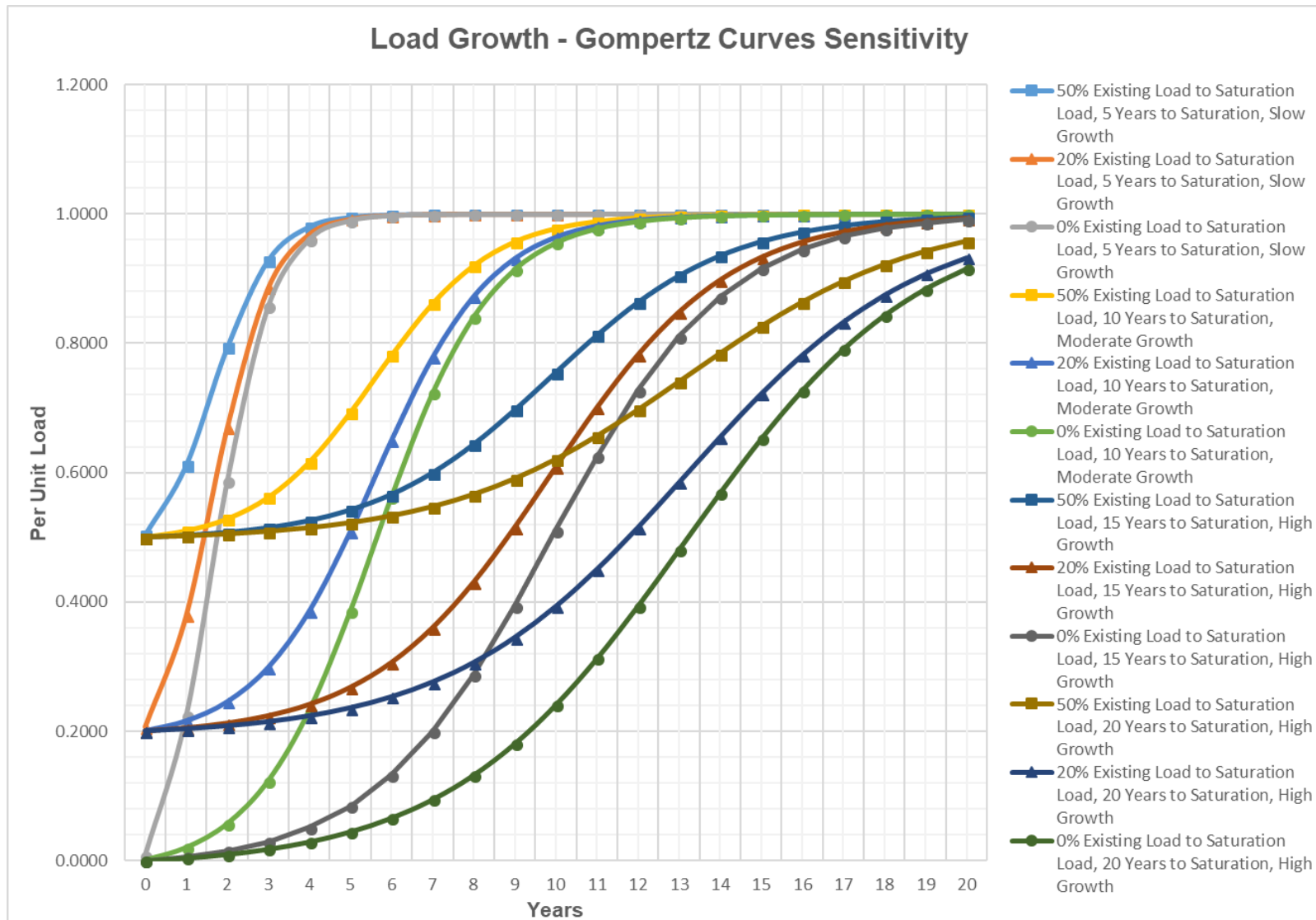


Figure 2-3: Gompertz Load Growth Curve Sensitivity

The exercise of load forecasting is an ongoing process which needs to be properly performed in order to ensure that there is sustainable electrical infrastructure. This commences with the proper residential load estimate requirement. The effects of an improperly calculated ADMD has detrimental effects not only on the operations of the electrical infrastructure network but in terms of the capital investment required to establish the electrical network. Consider the following scenario: an urban residential development consisting of 15 000 townhouse units with a properly calculated design ADMD of 2.5kVA due to the application of alternate water heating requirements other than conventional electrical resistance heating and non-electrical cooking requirement. This is compared with an ADMD of 4.0kVA which ignores the above-mentioned water heating and cooking requirements. The result of this scenario at the 20-year saturation point is provided in the table below:

Description	Residential Development with 15 000 Urban Townhouse Units								
	a			b			c		
A	0			0			0		
B	20			20			20		
C	1			5			10		
		MD			MD			MD	
Years	ADMD	2.5	4.0	ADMD	2.5	4.0	ADMD	2.5	4.0
0	0.0083	310	496	0.0004	14	23	0.0001	4	6
1	0.0447	1675	2680	0.0085	320	512	0.0042	159	254
2	0.0919	3448	5517	0.0199	745	1192	0.0100	376	602
3	0.1515	5683	9093	0.0355	1332	2131	0.0182	681	1089
4	0.2238	8394	13430	0.0569	2133	3413	0.0295	1105	1767
5	0.3076	11534	18454	0.0856	3211	5138	0.0451	1689	2703
6	0.3995	14981	23969	0.1235	4633	7412	0.0663	2488	3981
7	0.4947	18550	29681	0.1722	6459	10334	0.0950	3562	5699
8	0.5875	22030	35248	0.2327	8728	13964	0.1327	4977	7963
9	0.6728	25228	40365	0.3048	11431	18290	0.1812	6794	10871
10	0.7470	28012	44819	0.3866	14499	23198	0.2413	9050	14480
11	0.8086	30322	48515	0.4744	17790	28463	0.3130	11736	18778
12	0.8577	32165	51465	0.5631	21116	33786	0.3941	14780	23648
13	0.8957	33590	53744	0.6475	24282	38851	0.4811	18042	28867
14	0.9244	34665	55464	0.7234	27126	43402	0.5690	21336	34137
15	0.9456	35460	56737	0.7881	29553	47285	0.6524	24466	39146
16	0.9611	36041	57666	0.8409	31534	50454	0.7274	27276	43642
17	0.9723	36461	58338	0.8825	33093	52948	0.7912	29671	47474
18	0.9803	36762	58820	0.9143	34285	54855	0.8433	31625	50599
19	0.9861	36977	59164	0.9380	35176	56282	0.8843	33161	53057
20	0.9901	37130	59409	0.9555	35833	57332	0.9156	34335	54936
21	0.9930	37239	59582	0.9683	36310	58096	0.9390	35213	56341
22	0.9951	37316	59705	0.9774	36653	58646	0.9563	35859	57375
23	0.9965	37370	59792	0.9840	36900	59039	0.9688	36329	58126
24	0.9976	37408	59853	0.9887	37075	59320	0.9778	36667	58667
25	0.9983	37435	59896	0.9920	37199	59519	0.9842	36909	59055
26	0.9988	37454	59927	0.9943	37288	59660	0.9888	37082	59331
27	0.9991	37468	59949	0.9960	37350	59760	0.9921	37204	59527
28	0.9994	37477	59964	0.9972	37394	59831	0.9944	37291	59666
29	0.9996	37484	59974	0.9980	37425	59881	0.9961	37353	59764
30	0.9997	37489	59982	0.9986	37447	59916	0.9972	37396	59834

Table 2-7: Gompertz Load Growth Comparison at Different ADMD Design Levels

Important deductions from the previous table are summarized below:

- At the moderate growth rate, the saturation residential development load requirement is 35 833kVA compared to 57 332kVA at the improperly calculated ADMD.
- The repercussions of the additional 21 499kVA load requirement are as follows:
 - Unnecessary strain on the initial capital investment in which funds are sourced in the form of grants or loans.
 - In the case of grants, this puts extra strain on the national fiscus.

- In terms of the loan, interest will be repayable normally over a period of 20 years.
- Unnecessary strengthening and upgrades with associated costs of the bulk infrastructure to cater for the forecasted demand.
- Over design of electrical infrastructure which shall be under utilised.
- A 3 x 40MVA substation shall be required instead of a 2 x 40MVA substation.
- Strain on the operational expenditure due to no load-losses of the additional 40MVA transformer.

The information is represented graphically in the figure below:

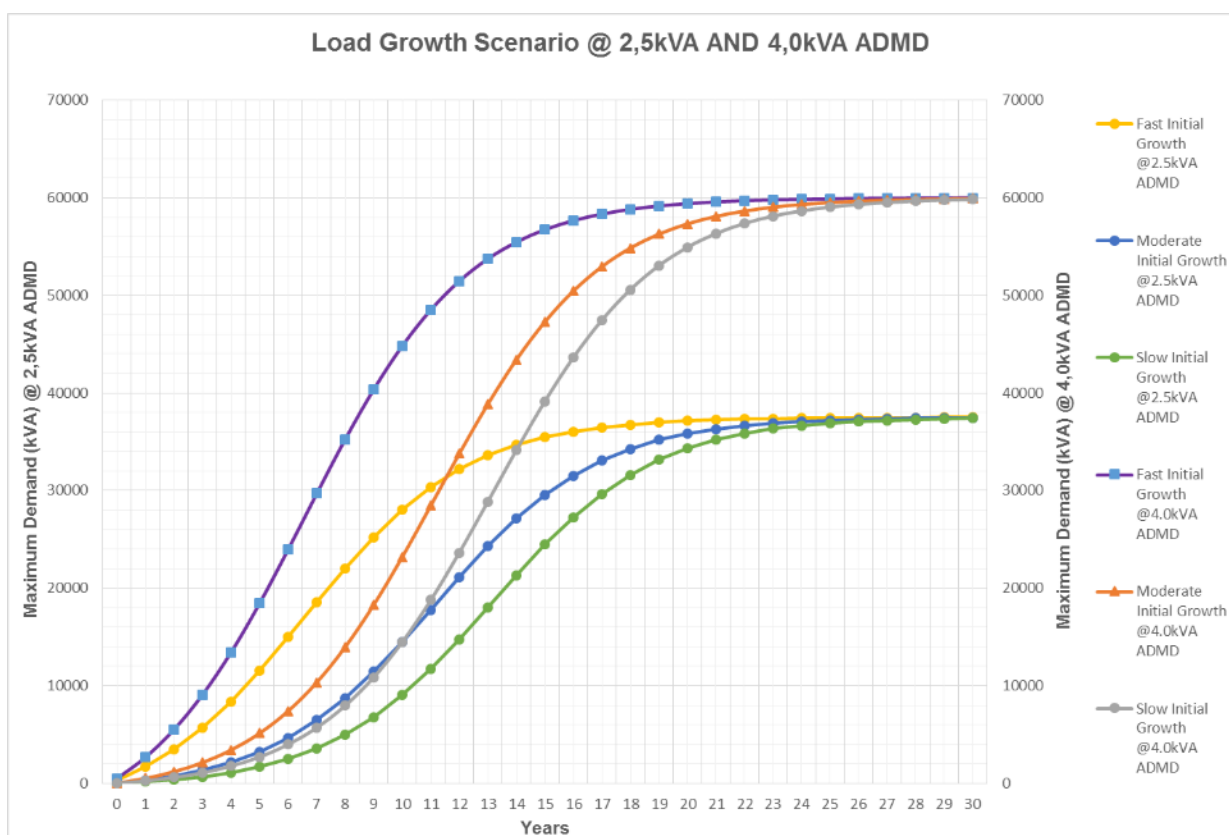


Figure 2-4: Gompertz Load Growth Curve Comparison at Different ADMD Design Levels

The proper application of the residential load estimation tools is of paramount importance as the ADMD which ultimately provides the residential development maximum demand has huge initial capital investment cost implications, increased operational expenses and under-utilised electrical infrastructure if calculated improperly.

2.3.4 Municipalities – Standards

There are licensed Municipalities which have electricity distribution licenses from NERSA for distribution of electricity within their municipal borders. In some instances, these Municipalities have developed their own standards which are applicable to their needs within their jurisdiction of supply. These developed standards and / or policies are predominately based on both the national SANS 507 standard and the Eskom standards. The Municipalities presented below are those which have their planning documents readily accessible on their websites.

2.3.4.1 City Power Johannesburg

City Power Johannesburg is the main electricity distributor within the City of Johannesburg Metropolitan Municipality. The areas within the boundaries of the Metropolitan Municipality in which City Power Johannesburg is not the licensed distributor are some areas of Sandton and Soweto. City Power Johannesburg has a consumer base varying from domestic to large power users with a total of approximately 360 000 consumers and a maximum demand of approximately 3 000 MW (City Power Johannesburg, 2017). The geographical supply area of City Power Johannesburg is provided in the figure below:

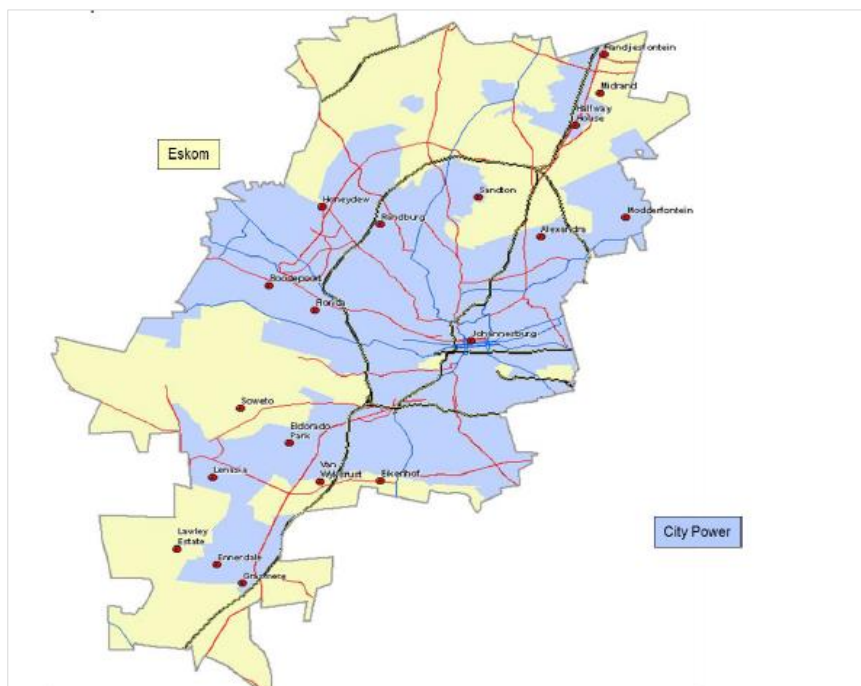


Figure 2-5: City Power Johannesburg Supply Area (City Power Johannesburg, 2017)

The municipal owned entity has a residential load estimation standard which is applied and implemented for all residential developments within their distribution license supply area. Through the Electrification Standard document CPSTAN_109 City Power uses the following to guide designers with regard to residential load estimation (City Power Johannesburg, 2014).

UNIT CATEGORY	Electrical Load	ADMD (kVA) @MSS LEVEL
Small($\leq 100\text{m}^2$)	50VA/m ²	5
Medium($100\text{m}^2 < 150\text{m}^2$)	50VA/m ²	7,5
High($\geq 150\text{m}^2$)	50VA/m ²	15

Table 2-8: City Power Johannesburg Residential Load Estimation Table (City Power Johannesburg, 2014)

It is worth noting that the recommended design values are much higher than those recommended in the national standard, the SANS 507.

2.3.4.2 City of Tshwane

City of Tshwane houses the administrative capital of the country. It services approximately 2.5 million residents within the boundaries of the Metropolitan Municipality (City of Tshwane, 2017).

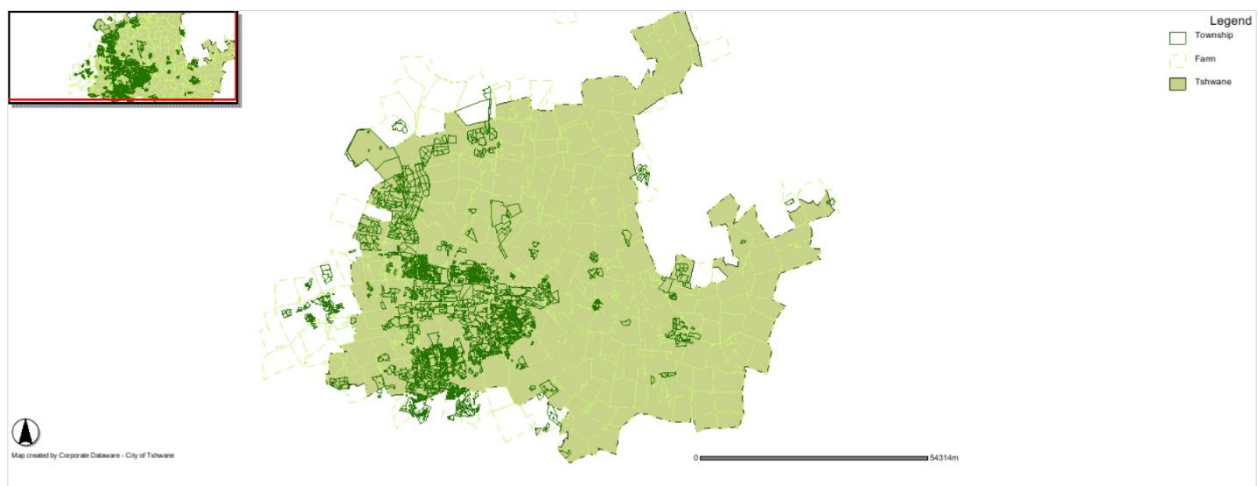


Figure 2-6: City of Tshwane Metropolitan Municipality Boundary (City of Tshwane, 2017)

The details of the load estimation for residential developments are provided as an annexure in the Municipality's Medium-Term Revenue and Expenditure Framework 2017/18 – Annexure D.

The Area factor is determined by the Executive Director: Energy and Electricity, and is indicative of the geographical load factor of the user area. The area factors are as follows:

- (i) For use in network designs for township development, scheme amendment and connection upgrading

Geographical load factor (ADMD)	Area factor
9 kVA ADMD (very high residential)	0,6522
7 kVA ADMD (high residential)	0,5072
5 kVA ADMD (standard residential)	0,3623
3,5 kVA ADMD (low cost housing)	0,2536
2 kVA ADMD (electricity for all)	0,1449
All other areas and all non residential applications	1,0000

- (ii) Only for use in network designs for township development

Geographical load factor (ADMD)	Area factor
18 kVA ADMD (very high residential) 80A three-phase	1,3043
15 kVA ADMD (very high residential) 60A three-phase	1,0869
12 kVA ADMD (very high residential) 40A three-phase	0,8696

Figure 2-7: City of Tshwane Residential Load Estimation (City of Tshwane, 2017)

2.3.4.3 City of Cape Town

In the Cape Town Metropolitan Municipality there are three licensed electricity distribution service providers, namely City of Cape Town Electricity Services Department, Eskom and African Explosives and Chemical Industries. The City of Cape Town Electricity Department is the main licensed distributor within the Metropolitan Municipality with a maximum demand of approximately 2 000 MW (City of Cape Town, 2016). The areas of distribution within the City are as demarcated below:



Figure 2-8: City of Cape Town Metropolitan Municipality Boundary (City of Cape Town, 2016)

The City of Cape Town Electrical Services Department has developed and refined load estimation based on the NRS 034:2001 (SANS 507) to their particular requirements. This was achieved by refining the urban up-market load class into additional sub-categories of the LSM10 and making provision for three-phase supply with the ADMD indicated as single phase.

The residential load estimation guideline document, LoadEstimationStandard_CTEF100 is readily available on the Metropolitan Municipality's website (City of Cape Town, 2014). These are provided in the table below:

1 Single Phase Loads																
Current Type			Load Parameters - 7 years							Load Parameters - 15 years						
Customer Load Class	SU LSM Class	Average Income (Gross R/month)	α	β	c	ADMD (kVA)	μ (A)	σ (A)	Var (A ²)	α	β	c	ADMD (kVA)	μ (A)	σ (A)	Var (A ²)
Informal Settlement	LSM 3 & 4	1 318 / 1 724	0,74	5,34	40	1,13	4,87	4,92	24,2	0,87	4,61	40	1,46	6,33	5,73	32,9
Township Area	LSM 5 & 6	2 421 / 3 897	-	-	-	-	-	-	-	0,98	2,41	40	2,66	11,54	8,65	74,8
Urban Residential I	LSM 7	5 859	-	-	-	-	-	-	-	1,22	2,96	60	4,04	17,48	11,98	143,5
Urban Residential II	LSM 8 & 9	8 053 / 10 732	-	-	-	-	-	-	-	1,05	1,70	60	5,31	22,98	15,06	226,8
Urban Upmarket I	LSM 10	15 931	-	-	-	-	-	-	-	0,94	1,25	60	5,96	25,80	16,64	276,9
2 Three Phase Loads (per phase)																
Urban Upmarket I	LSM 10	15 931	-	-	-	-	-	-	-	0,41	1,51	40	1,99	8,60	9,61	92,3
Urban Upmarket I	LSM 10	15 931	-	-	-	-	-	-	-	0,54	3,25	60	1,99	8,60	9,61	92,3
Urban Upmarket II	> LSM 10	> 15 931	-	-	-	-	-	-	-	0,32	0,81	40	2,65	11,47	12,39	153,5
Urban Upmarket II	> LSM 10	> 15 931	-	-	-	-	-	-	-	0,50	2,12	60	2,65	11,47	12,39	153,5
Urban Upmarket II	> LSM 10	> 15 931	-	-	-	-	-	-	-	0,59	3,53	80	2,65	11,47	12,39	153,5
Urban Upmarket II	> LSM 10	> 15 931	-	-	-	-	-	-	-	0,64	4,97	100	2,65	11,47	12,39	153,5
Assumptions: Escalation factor of mean value: 1,120 (Percentage escalation for Cape Peninsula region according to Table 3a Note 4 = 12%) Formula to calculate escalated standard deviation (single phase): $2,19 + 0,56\mu$ (Acceptable assumption where $\mu > 4,8$ A) Formula to calculate escalated standard deviation (per phase of three): $(2,19 + 0,56 * 3\mu)/\sqrt{3}$ (Acceptable assumption where $\mu > 4,8$ A) LSM Classes: The All Media and Product Survey Living Standard Measure (AMPS LSM) compiled on a regular basis by the SA Advertising Research Foundation (SAARF) was superseded in 2001 by the SAARF Universal Living Standard Measure (SU LSM). The new system makes use of 10 classes, with AMPS LSM 7 Low & High and AMPS LSM 8 Low & High becoming SU LSM 7, 8, 9 & 10 respectively. SAARF envisages that the range will eventually be extended beyond LSM 10. Average household income levels shown here for comparative purposes are in 2002 Rands. All income data collected at a later date should be deflated by the CPI to allow a direct comparison. (www.saarf.co.za) Customer Load Classes: Informal Settlement (7 years) - informal dwellings (built area typically less than 40 m²); area not subdivided & often unproclaimed Informal Settlement (15 years) - subdivided erven; informal dwellings or government subsidy low cost housing (built area typically less than 40 m²); no hot water cylinders Township Area - subdivided erven; (more than) government subsidy low cost housing (built area typically 50 - 80 m²); low to medium hot water cylinder penetration Urban Residential I - middle income housing (mostly blue-collar); single storey free-standing (built area typically 80 - 170 m²) or high density townhouse units; high hot water cylinder penetration Urban Residential II - middle income housing (mostly white-collar); single storey free-standing (built area typically 190 m²) or townhouse units within security complex (built area typically 80 - 150 m²) Urban Upmarket I - high income housing; large or multi-storey free-standing (built area typically 250 - 500 m²); often in area with desirable natural feature (eg a view) Urban Upmarket II - same as Urban Upmarket I, but for customer category beyond LSM 10; three phase supply required (assumption: diversified load 33% higher than for Urban Upmarket I)																

Table 2-9: City of Cape Town Residential Load Estimation Table (City of Cape Town, 2014)

The South African standards do not explicitly guide the designer on the topology to be used in the implementation of residential developments electrification. It only caters for the load parameters and on the basis of the load parameters, the topology can then be substantiated. The decision is normally left to the discretion of the designer / supply authority / developer. This dissertation seeks to provide a model which shall make it possible for any of the parties to come to a sustainable decision on the network topology to be implemented.

2.4 INTERNATIONAL DESIGN PLANNING

In this section, the design works and guidelines implemented by electricity distribution companies in developed countries is presented. The work is presented on the basis of the information available from the respective distribution companies' websites. The featured developed countries in which the residential electrification design planning is investigated are namely, Australia, the United Kingdom and the United States of America. It is worth noting that, in these developed countries, the generation, transmission and distribution of electricity occurs in a competitive free trade environment whereby there are respective national regulators at the different supply levels responsible for ensuring compliance with the statutory regulatory requirements (Brady, 1996; Butler, 2001).

2.4.1 Australia

The Australian electricity industry was disaggregated from the conventional vertically integrated model to a national electricity market model consisting of trading from electricity generation, transmission and distribution in 1997 (Brady, 1996). The electricity distribution companies featured in this dissertation are namely; AUSGrid, Energex, Ergon, Horizon Power, PowerCo, PowerWater, SA Power and Western Power.

2.4.1.1 AUSGrid

AUSGrid is one of the electricity distributors in the region of New South Wales, Australia. It is the electricity distributor in Sydney and the neighbouring cities (AUSGrid, 2018). The supply area of AUSGrid is indicated in the figure below.



Figure 2-9: AUSGrid Supply Area Boundary (AUSGrid, 2018)

The distribution company has a documented policy on the connection of premises which outlines the AUSGrid requirements for connection into their distribution network. A guideline in terms of the network topology to be implemented is indicated in tabular format in the policy (AUSGrid, 2014).

When the works are in ...	and the supply is ...	then the new network construction will be ...
urban area	HV	underground with at least one spare conduit per cable
	LV supplied underground	underground
	LV supplied overhead	underground In addition, a customer requiring only ASP/2 works will be required to make provision for underground connection to a future underground network for: • a commercial property frontage greater than 50 metres • a multiple residential development (e.g. home units or villa homes) not including duplexes overhead, using ABC construction for all other premises
non-urban area	HV	overhead, unless underground is practical and justified
	LV	overhead, using ABC construction, unless underground is practical and justified

When the new subdivision is ...	then the construction will be ...
residential	underground
commercial or industrial	underground
in a 1/100 flood prone area (as assessed and approved by Ausgrid on a case by case basis)	overhead

Table 2-10: AUSGrid New Network Topology Requirements (AUSGrid, 2014)

From the table, it is evident that a clear directive in terms of the requirements for new electrical infrastructure is required for different residential areas classifications. In terms of the residential load estimation namely, the ADMD, AUSGrid applies the Australian / New Zealand Standard (AS/NZS) 3000 – Wiring Rules for the estimation of the residential demand (AS/NZS, 2007). AUSGrid utilises the planning document, Design Information General Terms and Conditions. This planning document is provided to design services providers performing work within the AUSGrid distribution network. There is a section in which an allocation for the residential load estimate per region is provided and this is reproduced below (AUSGrid, 2018):

Area	ADMD Value
Upper Hunter	5.0kVA
Hunter	3.5kVA
Central Coast	3.5kVA
Sydney – North	3.5kVA
Sydney - South	3.5kVA

Table 2-11: AUSGrid Residential ADMD Table (AUSGrid, 2018)

It is worth noting that in the Design and Construction Standard for Underground Residential Distribution System (URDS) document, a diversity correction factor applicable to AUSGrid is provided as well (AUSGrid, 2015):

$$DCF = \left(8 + \frac{72}{100}N + \frac{95}{100}\sqrt{N} \right) \quad \dots (2) \text{ (AUSGrid, 2015)}$$

Where N is number of consumers

2.4.1.2 Energy Queensland

Energy Queensland is a group of companies generating, transmitting and distributing electricity within the state of Queensland. It consists of two main subsidiaries namely, Energex electricity distributor in South East Queensland and Ergon Energy which is the electricity distributor in regional Queensland (Energy Queensland, 2016).

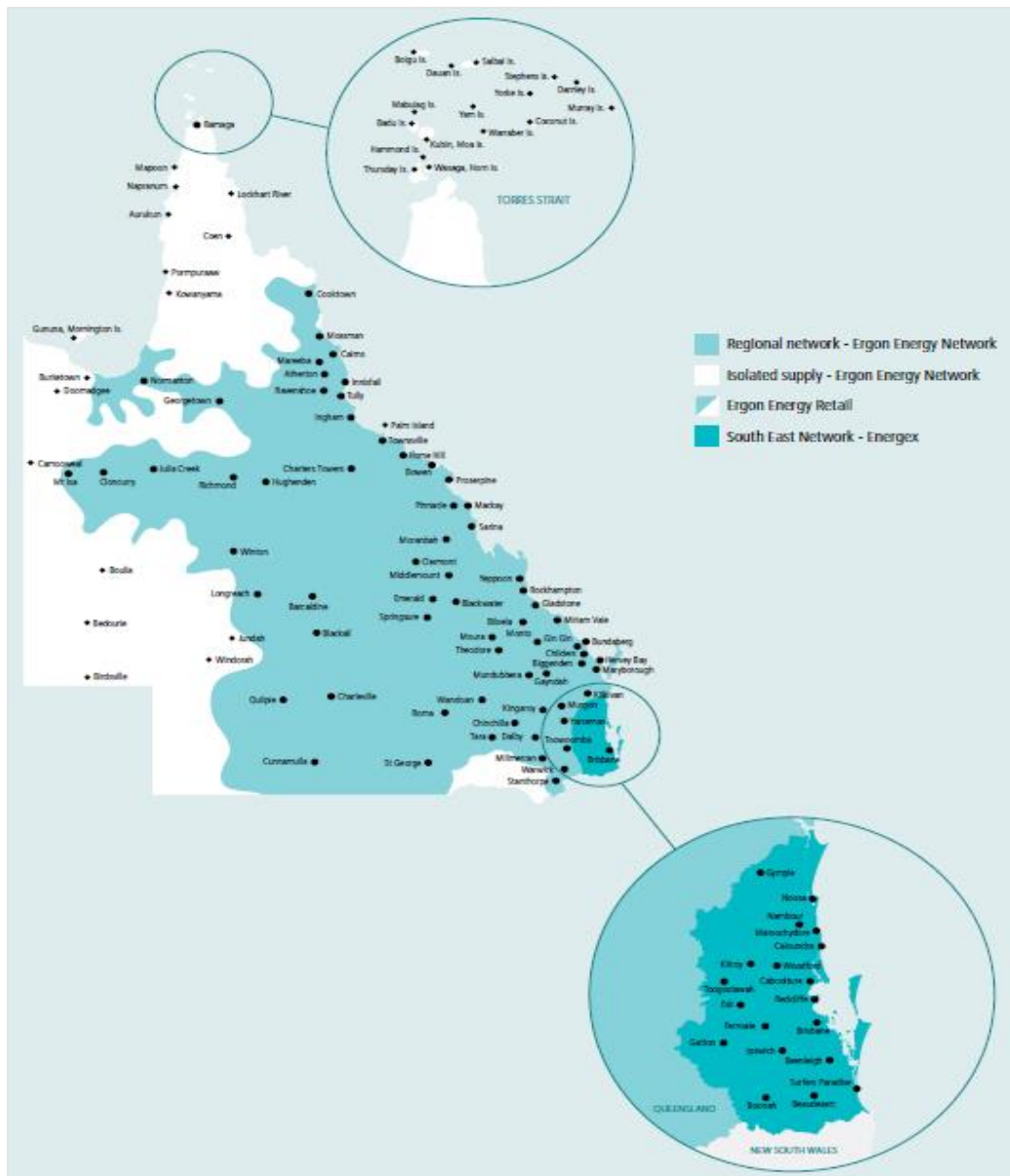


Figure 2-10: Energy Queensland Supply Area Boundary (Energy Queensland, 2016)

2.4.1.2.1 Energex

Energex is the electricity distributor in the South East Queensland including Brisbane and the surrounding areas.



Figure 2-11: Energex Supply Area Boundary (Energex, 2018)

In terms of the guidelines for the network design topology, the electricity distributor is not explicit, but it has standards in place which make provision for both overhead and underground residential networks. Energex's Supply and Planning Manual provide residential load estimation for the different consumer classifications including the diversity correction factor applicable in the distribution network (Energex, 2017).

Design ADMD kVA	Estate Category	Comments
3.0	Retirement Village Units, Cluster Housing, Duplex Units, Relocatable Homes, Units/Townhouses, Low Cost Housing	Applies to 2 or 3 bedroom houses, e.g. small low-set.
4.0	Middle/Upper income housing, High rise residential	Applies to 3 or 4 bedroom homes. THIS IS THE MAJORITY OF NEW ESTATES.
7.0	Prestige Housing/ Units/Townhouses	Applies to large prestige type housing and cluster developments
Notes: 1. Where gas cooking and water heating is used, values may be reduced by 1 kVA. A written request and supporting documentation shall be submitted to Energex. Approval for such shall be solely at Energex's discretion. 2. Where continuous electric hot water heating is used, increase the ADMD by 0.5 kVA. No increase is required for instantaneous hot water systems limited to 20 A single phase and 40 A three phase.		

Table 2-12: Energex Residential ADMD Table

$$DCF = \left(1 + \frac{1}{\sqrt{N}} \right) \quad \dots (3) \text{ (Energex, 2017)}$$

Where N is number of consumers

Interestingly, in a subsequent section in the document, the ADMD at the dwelling is provided as indicated in the table below (in the document they refer to $ADMD_{(inf)}$, which is the ADMD whereby the diversity approaches 1, that is, ADMD is constant). At DCF (1) the respective $ADMD_{(inf)}$ is small (3 – 5kVA), medium (5 – 7.5kVA) and large (7.5 – 10kVA).

Individual dwellings	Small 6 – 10 kVA Medium 10 – 15 kVA Large 15 – 20 kVA
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Table 2-13: Energex Residential ADMD at the Individual Dwelling (Energex, 2016)

The design parameters provided in the Subdivision Standard – Developer Design and Construct Estate document are also similar to the above and defined as follows (Energex, 2016):

- Standard Residential Developments – ADMD 4.5kVA with standard deviation of 50%.
- Prestige Housing – ADMD 7.0kVA.

2.4.1.2.2 Ergon Energy

Ergon Energy is the electricity distributor in the regional areas of the state of Queensland and Torres Saint servicing approximately 750 000 consumers (Energy Queensland, 2016).



Figure 2-12: Ergon Energy Supply Area Boundary (Energy Queensland, 2016)

The residential load estimation within the electricity distributor's supply area makes provision for conventional housing developments. The load estimation is based on historical data inclusive of the provision for future demand load growth. In the Standard for Distribution Line Design Underground document, the ADMD for the different areas within regional Queensland is provided (Ergon Energy, 2016). It must be noted that the document is silent on the diversity correction factor and only refers to confidence factor for the voltage drop calculations.

Area Description	Design ADMD	Confidence Factor
South West, Wide Bay and Capriconia	4kVA	2
North, Far North and Mackay	5kVA	

Table 2-14: Ergon Energy Residential ADMD Table (Ergon Energy, 2016)

2.4.1.3 Horizon Power

Horizon Power is the electricity distributor in the North, South and Mid-West regions servicing approximately 50 000 customers in regional areas of Western Australia (Horizon Power, 2018).



Figure 2-13: Horizon Power Supply Area Boundary (Horizon Power, 2018)

Horizon Power services its customers through both overhead and underground networks. In their information document, Electrical Design Information for Distribution Networks – After Diversity Maximum Demand, different ADMD values are provided for the areas within the distribution supply area (Horizon Power, 2013).

Towns	Residential ADMD (kVA)
East Kimberley	
Halls Creek, Kalumburu, Kununurra, Lake Argyle, Wyndham	6
Warmun	4
West Kimberley	
Broome, Derby, Fitzroy Crossing	6
Ardyaloon, Beagle Bay, Camballin / Looma, Camballin / Looma, Yungngora	4
East Pilbara	
Port Hedland, South Hedland	10
Marble Bar, Nullagine	4
West Pilbara	
Karratha – Single Lot, Onslow, Point Samson	10
Karratha – Duplex	7.5
Roebourne	6
Karratha – Triplex	5.5
Karratha – Quadr'ex	3.5
Gascoyne/Midwest	
Carnarvon, Coral bay, Cue, Laverton, Leonora, Meekatharra, Menzies, Mt Magnet	6
Denham, Gascoyne Junction, Sandstone, Wiluna, Yalgoo	4
Esperance	
Esperance, Hopetoun, Norseman	3

Table 2-15: Horizon Power Residential ADMD Table (Horizon Power, 2013)

These design values are based on measured ADMD values with provision for potential future growth. It is worth noting that, in the document diversity correction factors are included for up to 60 and less consumers.

Number of Customers	Diversity Factor	Number of Customers	Diversity Factor	Number of Customers	Diversity Factor
1	3.00	8	1.71	21-23	1.42
2	2.57	9	1.69	24-26	1.40
3	2.20	10	1.64	27-29	1.38
4	2.00	11	1.61	30-59	1.37
5	1.89	12-14	1.57	=<60	1.0
6	1.80	15-17	1.50		
7	1.74	18-20	1.46		

Table 2-16: Horizon Power Diversity Correction Factor Table (Horizon Power, 2013)

2.4.1.4 Power and Water Corporation

Power and Water Corporation is responsible for the generation, transmission and distribution of electricity in the Northern Territory of Australia surrounded by Queensland in the East, Western Australia in the West and South Australia in the South. The utility service provider services approximately 85 000 consumers within its supply area (Power and Water Corporation, 2017).

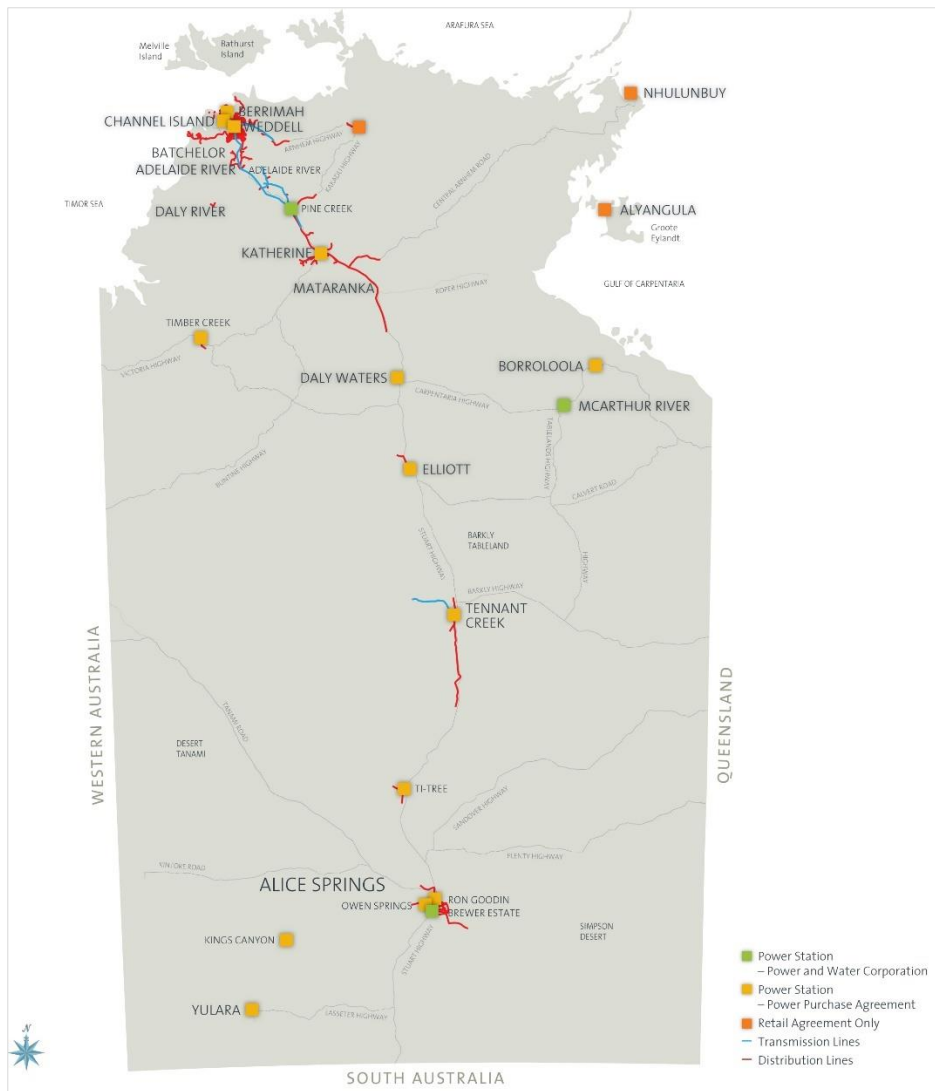


Figure 2-14: Power and Water Corporation Supply Area Boundary (Power and Water Corporation, 2017)

In the planning document, Design and Construction of Network Assets – General Requirements, the design ADMD is provided for new residential developments within the Power and Water Corporation supply area (Power and Water Corporation, 2008). It is interesting to note that, the document states that all new urban residential developments shall consist of underground network reticulation. Part of their standards indicate the following:

- No new overhead distribution networks are permitted within residential areas in main centres.
- The utility might require underground or Aerial Bundle Conductor distribution networks in other centres or rural areas.
- Bare open wire low voltage reticulation is not permitted in new urban residential developments.

The ADMD is provided for two different lots only, namely, normal residential developments at 4.5kVA and high cost residential developments at 7kVA. Although the diversity correction factor is not explicitly provided, the diversified load is provided for up to 4 lots zoned as Residential 1 (R1) lots. Hence the diversity correction factor for one lot can be deduced to be ~2.4 for normal residential developments and 2.0 for high cost residential developments.

4.5 kVA/lot		7 kVA/lot	
Number of Lots	Diversified Loading	Number of Lots	Diversified Loading
1 x R1 lot	11 kVA ^α	1 x R1 lot	14 kVA ^α
2 x R1 lots	18 kVA	2 x R1 lots	24 kVA
3 x R1 lots	24 kVA	3 x R1 lots	33 kVA
4 x R1 lots	29 kVA	4 x R1 lots	43 kVA
Additional lots	4.5 kVA	Additional lots	7 kVA

^α This load will be assumed to be at the end of each radial run, and shall be deemed to be single phase. The remaining load shall be considered to be balanced three phase load.

Table 2-17: PowerWater Residential Areas ADMD Table (Power and Water Corporation, 2008)

2.4.1.5 Western Power

Western Power is responsible for the generation, transmission and distribution of electricity in the major areas of Western Australia servicing approximately 1.1 million consumers (Western Power, 2017a).



Figure 2-15: Western Power Supply Area Boundary (Western Power, 2017a)

In the utility's Underground Distribution Schemes Manual document, the residential development design ADMD is provided together with an online ADMD calculator (Western Power, 2017b). In calculating the ADMD the calculator considers the size of the lot (erf), land value and location (suburb). The design ADMD which gives the maximum demand is provided by the formula which includes the diversity correction factor to cater for less than 50 consumers.

$$MD = DCF \times ADMD \times N \quad \dots (4)$$

$$DCF = \left(1 + \frac{1}{N} \right) \quad \dots (5)$$

Where N is number of consumers

It is worth noting that when the number of consumers exceeds 50, the ADMD is simply provided by dividing the maximum demand with the number of customers.

Lot price / dwelling	Single to quadruplex	Less than 10 units	More than 10 units
\$512,000 or less	4.7 kVA	3.5 kVA	3.1 kVA
\$512,001 to \$1,024,000	6.2 kVA	4.4 kVA	4.0 kVA
Above \$1,024,000	8.7 kVA	5.9 kVA	5.4 kVA

Table 2-18: Western Power Residential ADMD Table (Western Power, 2018)

2.4.2 United Kingdom

The United Kingdom electricity supply industry was privatised through the adoption and implementation of the Electricity Act 1989 – this made way for private generation, transmission and distribution of electricity (Butler, 2001). The electricity distributions companies presented in this dissertation are namely, the Northern Powergrid, Scotland Power Energy Networks and the United Kingdom Power Networks.

2.4.2.1 Northern Powergrid

The Northern Powergrid is an electricity distributor in the North East of England and Yorkshire supplying a combined total of approximately 3.9 million residential and business consumers within its supply area (Northern Powergrid, 2014).

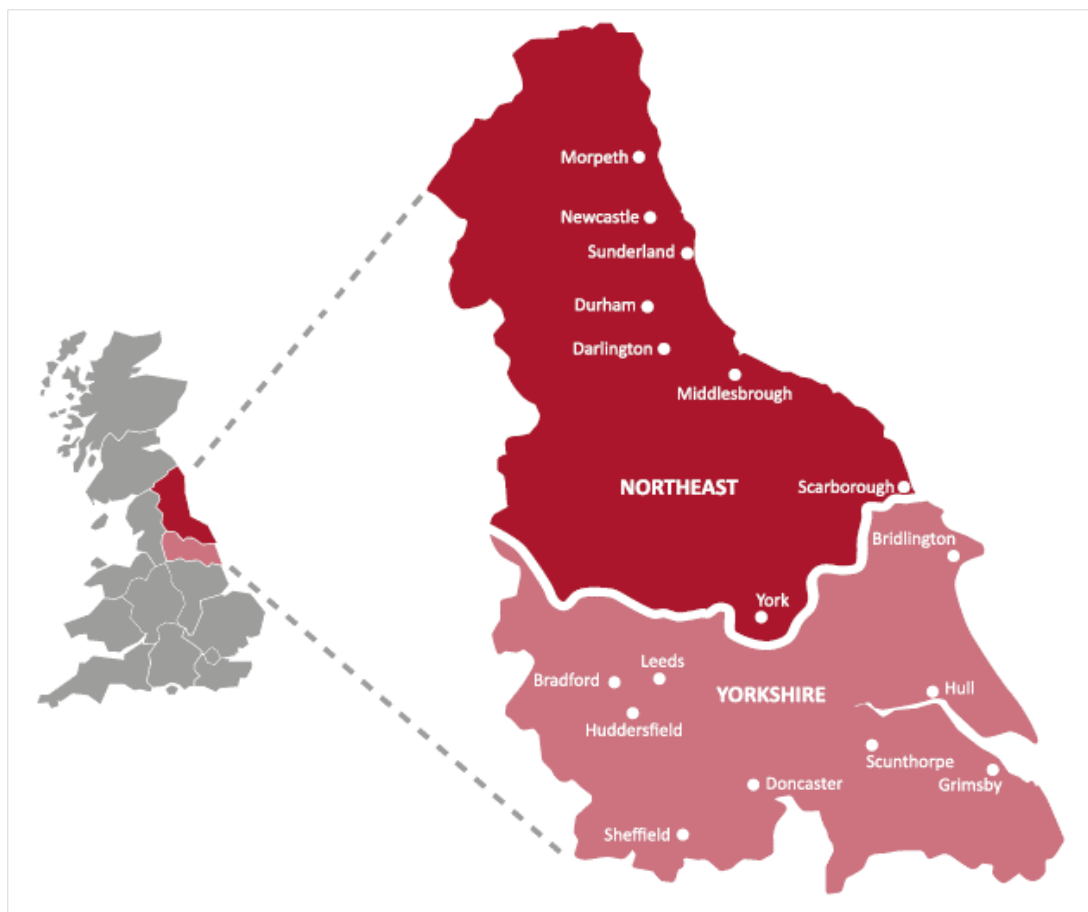


Figure 2-16: Northern Powergrid Supply Area Boundary (Northern Powergrid, 2014)

The utility's document, Code of Practice for the Economic Development of the LV System, an underground system is preferred instead of overhead system unless it is uneconomical in urban areas (Northern Powergrid, 2017). In terms of the ADMD, the documents provide three design scenarios namely, domestic, domestic including heating as well as domestic and electric vehicle charging. These are all illustrated in the table below:

Domestic Classification	ADMD
General Domestic	$4.6n^{-0.22}$
General Domestic plus Water Heating	$6.093n^{-0.25}$
General Domestic plus Electric Vehicle Charging	$3.918n^{-0.7261} + 3.569$

Table 2-19: Northern Powergrid Domestic ADMD Table (Northern Powergrid, 2017)

2.4.2.2 Scotland Power Energy Networks

Scotland Power Energy Networks is a licensed distributor in Scotland (Scotland Power Distribution), England and Wales (Scotland Power Manweb) with a combined customer base of approximately 3.5 million residential and business consumers (Scotland Power Energy Networks, 2017).

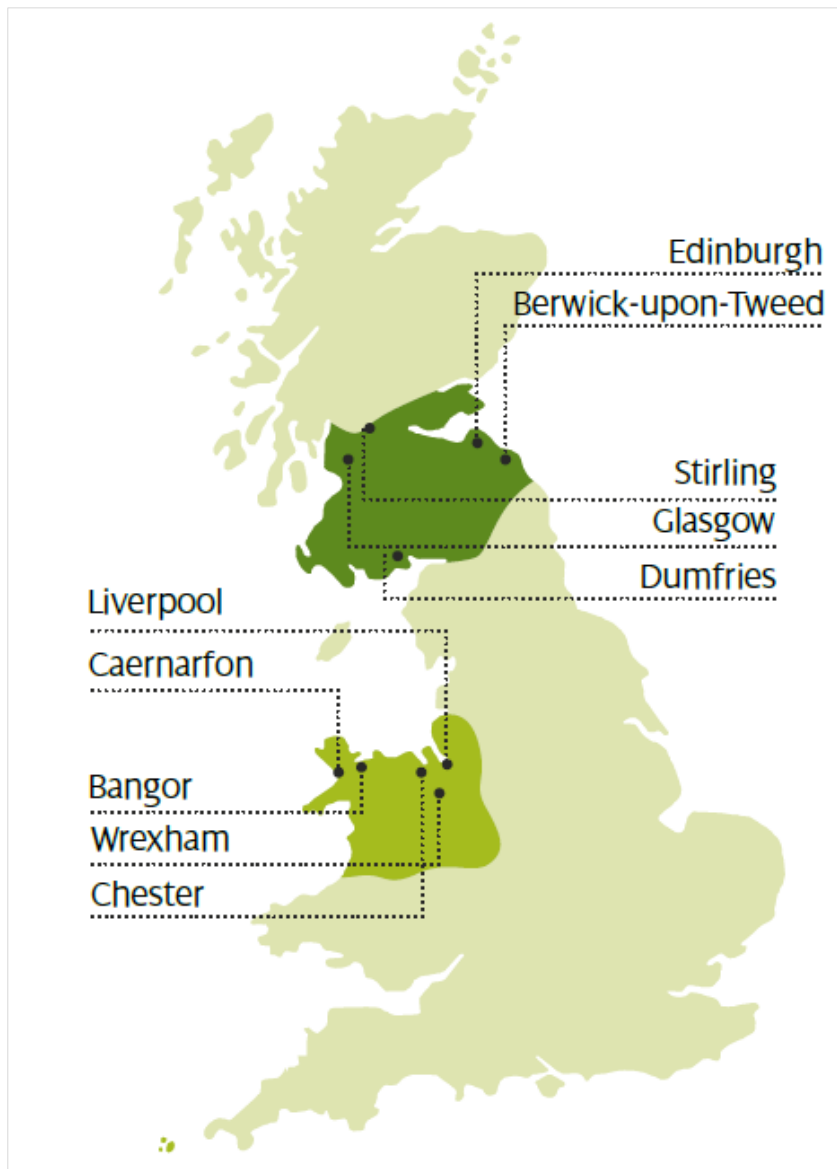


Figure 2-17: Scotland Power Energy Networks Supply Area Boundary (Scotland Power Energy Networks, 2017)

The utility has a guiding document for load estimation – Framework for Design and Planning of LV Housing Developments (Scotland Power Energy Networks, 2016). In the document a fixed ADMD value is provided for two scenarios, i) with water heating and ii) without water heating.

The ADMD is also grouped in terms of the type of property to be catered for. All of this is summarised in the tables below:

Type of Heating	Type of House	Annual Consumption (kWh)	ADMD (kW)
Gas Hot Water and Central Heating and 3kW Immersion Heater	5 Bedroom (or larger) Property	5000	2.0
	3 Bedroom Detached property or 4 Bedroom property	4250	1.5
	1 Bedroom/2 Bedroom property or 3 Bedroom Non-Detached property	3500	1.0

Table 2-20: Scotland Power Energy Networks ADMD Table – Non-Electric Heated Dwellings (Scotland Power Energy Networks, 2016)

c	H	ADMD (kW) (to be rounded up to nearest 0.5kW)
Storage radiators / panel heaters	Total heating load including water heating, storage and panel	$0.6H + 2$
Storage radiators / panel heaters in dwelling with high thermal efficiency	Total heating load including water heating, storage and panel	$0.5H + 2$
Storage central heating boilers	Total value of installed storage space heating only	$H + 3$
Heat Pump (air or ground source)	Total value of installed storage space heating only	$H + 3$

Table 2-21: Scotland Power Energy Networks ADMD Table – Electric Heated Dwellings (Scotland Power Energy Networks, 2016)

2.4.2.3 Scottish and Southern Electricity Networks

The Scottish and Southern Electricity Networks is a licensed distributor in Northern Scotland and the central regions of Southern England servicing a total of approximately 3.7 million residential and business consumers (Scottish and Southern Electricity Networks, 2017).

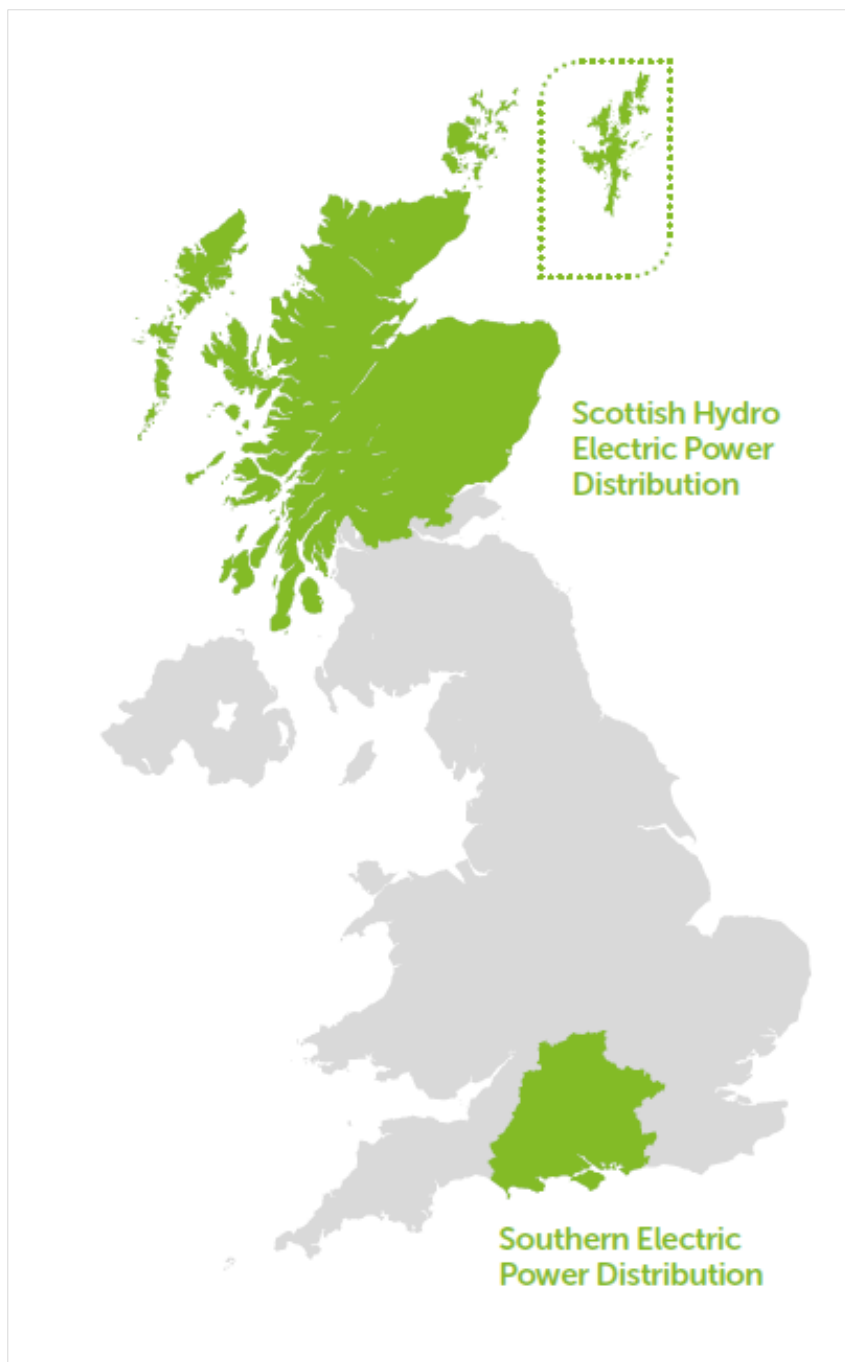


Figure 2-18: Scottish and Southern Electricity Networks Supply Area Boundary (Scottish and Southern Electricity Networks, 2017)

The utility uses the guideline document, Planning and Design Guidance for Low Voltage and 11kV Secondary Distribution Networks document for the purposes of residential load estimation (Scottish and Southern Electricity Networks, 2016). The ADMD for non-electric heating is classified according to the property type, consumer classification and annual energy consumption for the specific property.

Non-Electric	Annual Units		A.D.M.D kVA	
	Cons type	Day Units	Day	Night
3-Bed	URMC	4,500	2.25	0.5
4-Bed	URMC	5000	2.25	0.5
5-Bed	URMC	6000	2.25	0.5
For existing network reassessment only				
Electric			2.8	10.0

Table 2-22: Scottish and Southern Electricity Networks ADMD Table (Scottish and Southern Electricity Networks, 2016)

For the case of residential properties with off-peak heating, the individual ADMD is provided through a graphical representation which is included in the planning document. The ADMD makes provision for a night time (peak) ADMD and a daytime ADMD which caters for unrestricted heating load during the day.

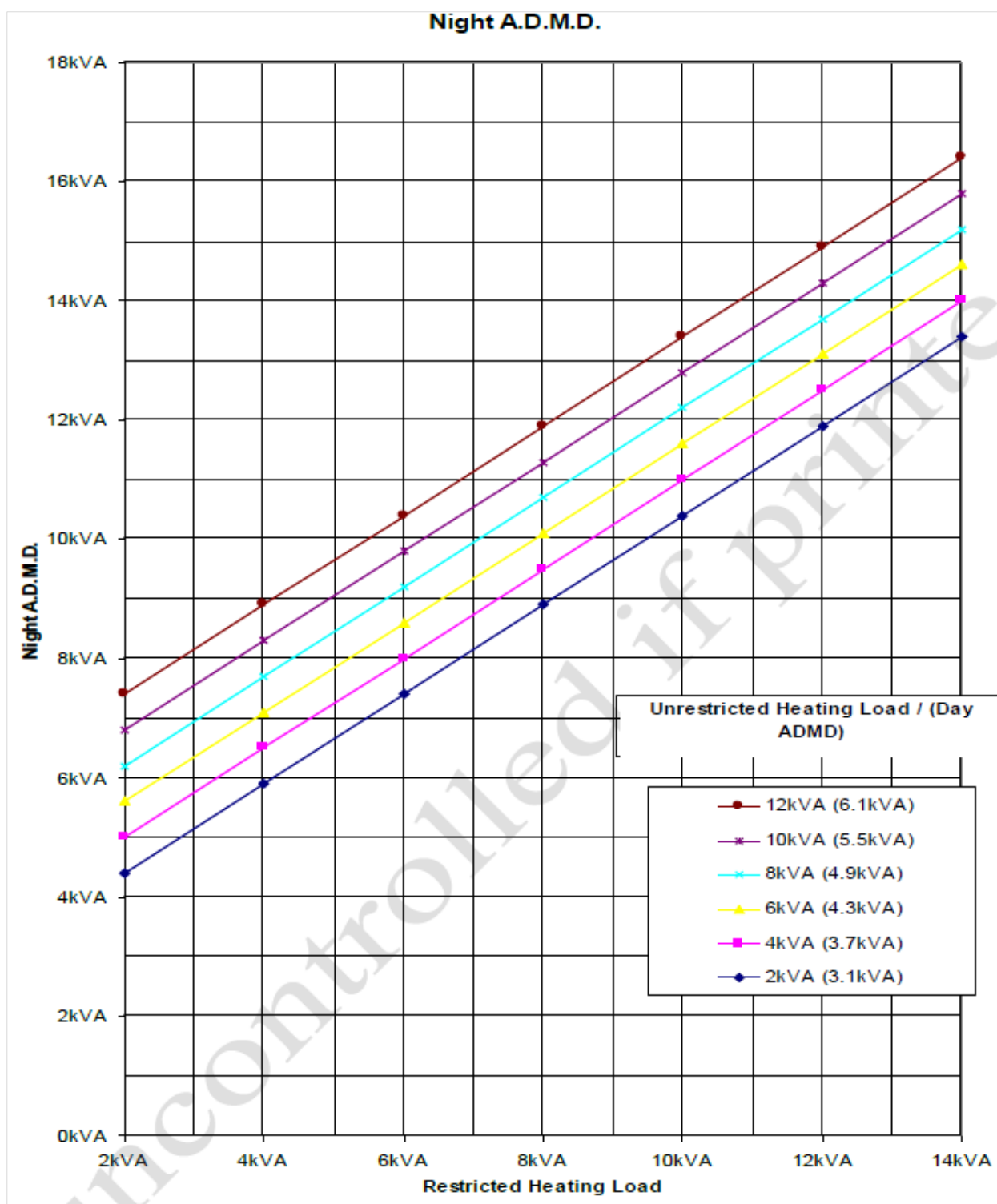


Figure 2-19: Scottish and Southern Electricity ADMD Graph for Off-Peak Heating
(Scottish and Southern Electricity Networks, 2016)

2.4.2.4 Western Power Distribution Networks

The utility is the licensed electricity distributor in the Midlands of England, the South West and South of Wales with a consumer base of approximately 7.8 million residential and business consumers (Western Power Distribution Networks, 2014).

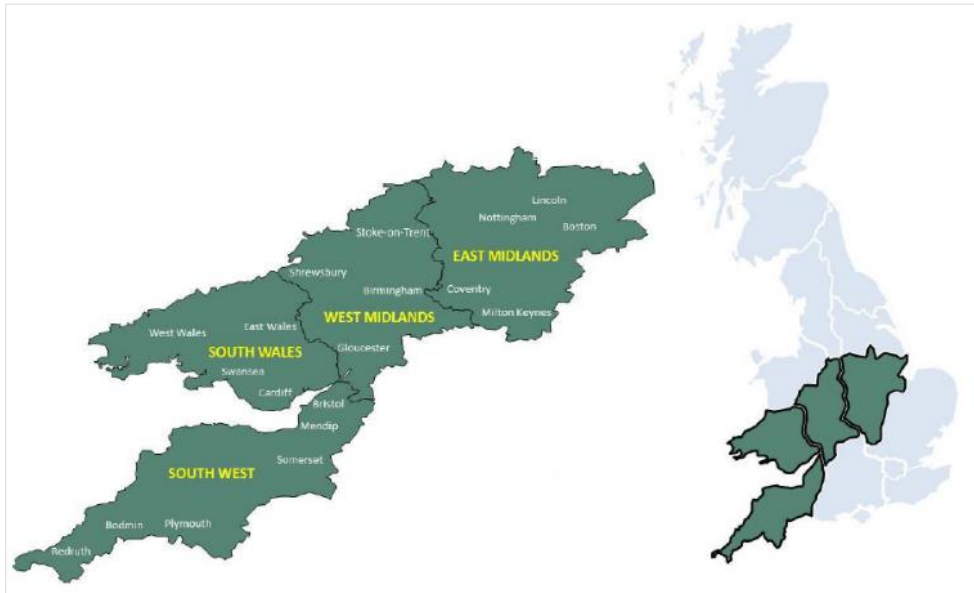


Figure 2-20: Western Power Distribution Networks Supply Area Boundary (Western Power Distribution Networks, 2014)

Residential load estimation for the distributor is guided by the document, Design of Low Voltage Connections (Western Power Distribution Networks, 2017). The ADMD is classified in terms of the property type and heating requirements.

Description of Heating	Windebut Profile	1 Bedroom		2 Bedroom		3 Bedroom		4 Bedroom		5 Bedroom	
		Day kW	Night kW	Day kW	Night kW	Day kW	Night kW	Day kW	Night kW	Day kW	Night kW
Gas Central Heating	OFFER 1	0.9+A+E		1.3+A+E		1.7+A+E		2.0+A+E		2.3+A+E	
Electric E7 Heating	OFFER 2	1.3 +A+E	1.3 +B+C+E	1.8 +A+E	2.0 +B+C+E	2.3 +A+E	2.5 +B+C+E	2.7 +A+E	2.8 +B+C+E	3.1 +A+E	2.9 +B+C+E
Electric E10 Heating	ECO10	1.3+D+E		1.8+D+E		2.3+D+E		2.7+D+E		2.9+D+E	
Heat Pumps	OFFER 1	0.9+D+E		1.3+D+E		1.7+D+E		2.0+D+E		2.3+D+E	
Other Non-electric Central Heating	OFFER 1	0.9+A+E		1.3+A+E		1.7+A+E		2.0+A+E		2.3+A+E	

Where:

A = 0.2 x total kW rating of any direct heating.

B = 1.0 x total kW rating of any direct heating.

C = 1.0 x total kW rating of any “off peak” heating (e.g. storage heaters).

D = 1.0 x total kW rating of the electric heating and electric water heating load. For existing connections add together the unrestricted and restricted units together.

E = 0.5 x total kW rating of any electric vehicle charging points.

Table 2-23: Western Power Distribution Networks ADMD Table (Western Power Distribution Networks, 2017)

2.4.2.5 Electricity North West

The utility is the licensed distributor in the North West of England servicing a total of approximately 2.4 million residential and business consumers (Electricity North West, 2018).



Figure 2-21: Electricity North West Supply Area Boundary (Electricity North West, 2018)

The residential load estimation by the utility is guided through the document, Design for New Connections for Housing Development (Electricity North West, 2008). The ADMD is also provided in terms of the property type, as well as a night and day time ADMD value.

Property Type	ADMD per customer (kW)	
	Day	Night
Small Non-Electric Non-Detached	1.0	0.4
Non-Electric Detached	1.4	0.6
Electric Heating (installed in each of a group of average-sized properties). (This takes account of the large diversity, where electric heating is not subject to a restricted-hour tariff.) See 3.8.2 below regarding high density housing.	3.4	2.4
Off-peak Tariff, eg E7 (where substantial storage heating load is switched to take advantage of low 'off-peak' rates)	1.5	0.8 (aggregate installed water and storage heating capacity kW) + 0.5
Off-peak Tariff with afternoon boost (where substantial storage heating load is switched to take advantage of low or 'off-peak' rates)	3.4	0.8 (aggregate installed water and storage heating capacity kW) + 0.5
Two Rate Tariff, eg E10 with afternoon, evening and night cheaper rates (where the tariff provides an incentive to concentrate usage in the cheaper periods, notably in the evening)	0.6 (maximum space heating available 07:00 to 24:00 plus water heating kW) + 2 *	0.6 (maximum space heating available 00:00 to 07:00 plus water heating kW) + 0.5 *
Air conditioning (where installed in each of a group of properties)	Depending on the likely operating regime, add an appropriate fraction (say 50%) of the installed cooling load to the above daytime ADMD values.	

Table 2-24: Electricity North West ADMD Table (Electricity North West, 2008)

2.4.2.6 United Kingdom Power Networks

The United Kingdom Power Networks consists of three main licensed distributors in the UK namely, the London Power Networks, Eastern Power Networks and South Eastern Power Networks. These utilities combined serve a total of approximately 8 million consumers (United Kingdom Power Networks, 2014).

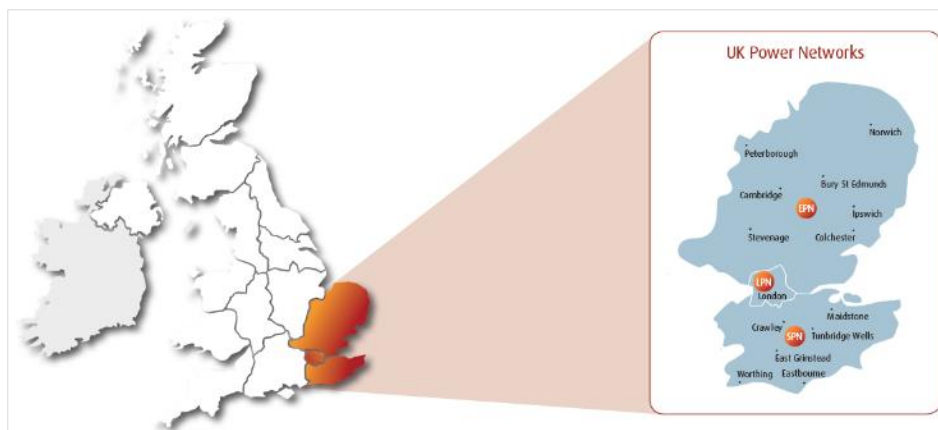


Figure 2-22: United Kingdom Power Networks Supply Area Boundary (United Kingdom Power Networks, 2014)

The utility's residential load estimation is guided by the LV Design and Planning document, titled, LV Network Design Standard (United Kingdom Power Networks, 2017). The ADMD is given for different dwelling types, heating requirement and the demand is provided for day as well a night time demand.

Type of Property	Day	Night
1-2 Bedroom with Gas Central Heating	1.2	0.3
3 Bedroom with Gas Central Heating	1.5	0.3
4 Bedroom with Gas Central Heating	1.8	0.5
5+ Bedroom with Gas Central Heating	2.4	0.5
1-2 Bedroom with Other Central Heating	1.5	2
3 Bedroom with Other Central Heating	1.9	2.5
4 Bedroom with Other Central Heating	2.1	3
5+ Bedroom with Other Central Heating	3.1	2.3
E7 Property with 1 Heater & Water Heating	2.2	2.1
E7 Property with 2 Heater & Water Heating	2.5	4.6
E7 Property with 3 Heater & Water Heating	2.8	10
E7 Property with 4 Heater & Water Heating	3.4	12.5
15kW Electric Boiler (On E7)	4.5	16.2
19kW Electric Boiler (On E7)	5.7	19.8

Table 2-25: United Kingdom Power Networks ADMD Table (United Kingdom Power Networks, 2017)

2.4.3 United States of America

The United States of America utilises the single-phase supply configuration in the secondary networks – this is in comparison with the three-phase supply configuration on secondary networks in Australia, the United Kingdom and of which South Africa has adopted.

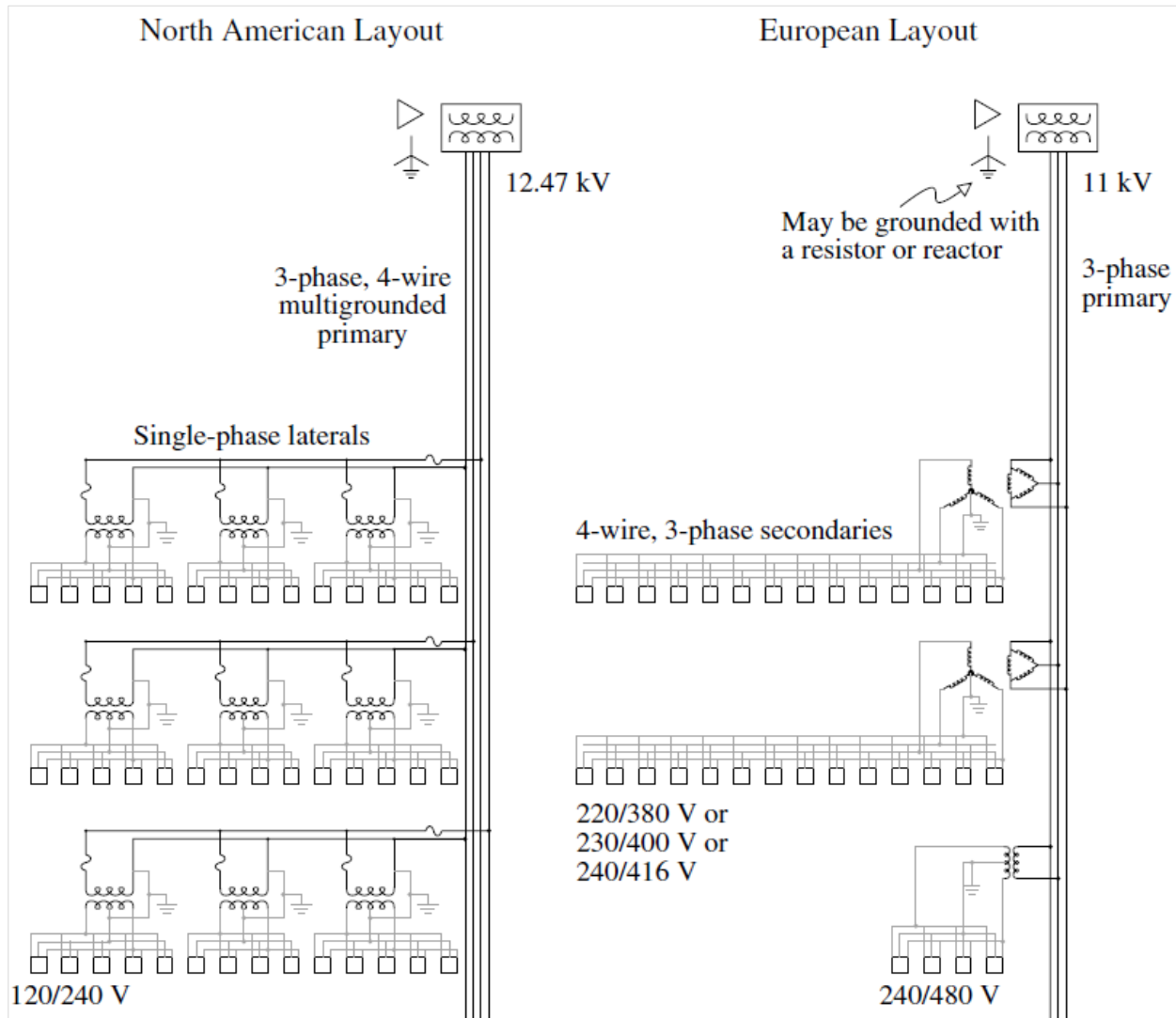


Figure 2-23: North American Supply Configuration versus European Supply Configuration (Short, 2004)

In a single-phase supply configuration power is transmitted over one phase whereas in a three-phase supply configuration, power is transmitted over three phases. This results in large transformers (100kVA – 1000kVA) used in three-phase systems compared to smaller transformers (16kVA – 50kVA) in single-phase systems for residential applications (Short, 2004). It is not the objective of this dissertation to further discuss the different secondary network configurations.

In terms of load estimation, the National Fire Protection Association (NFPA) 70: National Electrical Code (NEC) 2011 is the reference document for residential load estimation similar to the SANS 10142 and AS/NZS 3000. The electric code essentially implements appliance load modelling techniques which uses demand factors to estimate the load per residential dwelling (NFPA, 2011). In residential developments, diversity factors are subsequently applied in the low voltage feeder design.

2.4.3.1 SaskPower

SaskPower has developed residential diversified load tables which they implement in the low voltage designs and transformer sizing calculations (SaskPower, 2013). The tables were developed from load studies taken at 60-minute intervals for transformer sizing, 5-minute intervals for low voltage design and standards developed by the utility. The table applied for the low voltage design, which has the main constraint as the voltage drop is provided below.

Number of Residential Customers	Div. Demand KVA	Expected Current Amps	Number of Residential Customers	Div. Demand KVA	Expected Current Amps
1	15	63	13	57	238
2	20	83	14	62	258
3	24*	100	15	65	271
4	28	117	16	68	283
5	35	146	17	70	292
6	42	175	18	74*	308
7	44	183	19	77	321
8	46	192	20	80	333
9	48	200	21	83	346
10	50*	208	22	86	358
11	53	221	23	89	371
12	56	233	24	92*	383

*Items in bold correspond to available padmount transformer sizes (25, 50, 75, and 100KVA)

Table 2-26: SaskPower Low Voltage Design Diversified Demand Table (SaskPower, 2013)

2.4.3.2 San Diego Gas & Electric Company

The San Diego Gas & Electric Company applies residential demand tables in order to provide residential development load estimates. The tables cater for different load requirement per dwelling – the dwelling load requirement is calculated using the appliance load modelling and the respective demand factor of the appliance and / or circuit.

The diversity factors table for the implementation of the low voltage design are provided (San Diego Gas & Electric Company, 2002).

Demand Categories	Demand Factor	Connected Appliances	Connected kW Demand per Unit Estimate (c)
LIGHTS	.50	internal lighting	4–6
HVAC (heat pump)	.50	3 to 7–1/2 ton single or multiple units	1.35kW/ton
MAJOR APPLIANCES	.50	range water heater water heater (quick recovery) clothes dryer dishwasher heat strip	8–12 ea. 4.5 ea. 9 ea. 5.5 ea. 1.2 ea. 5–15 ea.
EXTERIOR LOADS	.50	tennis court lighting swimming pool equipment exterior lighting	varies varies varies
OTHER LOADS	.40	convenience outlets wine cellar sauna small motor load	varies

Dwelling Type	Square Footage	KW DEMAND CATEGORIES (a)					
		Base Load	Air Cond.	Elec. Water Heating	Elec. Heating	Elec. Heating & Water Heating	A/C & Elec. Water Heating
single–family detached	0–1299	3.0	5.0	5.0	4.0	6.5	6.0
	1300–1999	4.0	6.0	6.0	5.0	7.5	7.0
	2000–2999	4.5	7.0	7.0	6.0	8.0	8.0
single–family attached (condo/townhouse)	0–1299	3.0	4.0	5.0	4.0	6.5	5.0
	1300–1999	4.0	5.0	6.0	5.0	7.5	6.0
	2000–2999	4.5	5.5	6.5	5.5	8.0	6.5
multi–family (apartments)	0–1299	1.5	3.5	3.5	4.0	6.5	4.5
	1300–1999	2.0	4.0	4.0	4.5	7.0	5.0
mobile–homes	0–1299	2.5	5.0	(b)	5.0	(b)	(b)
	1300–1999	3.0	6.0		6.0		

Number Of Customers	Diversity factor categories		
	Base load electric heating electric water heating	Air conditioning	
		SF detached	MF, SF attached
1–2	1.00	1.00	1.00
3–4	.75	0.85	0.70
5–7	.65	0.80	0.65
8–14	.55	0.75	0.65
15 and above	.50	0.70	0.60

Table 2-27: San Diego Gas & Electric Company Load Estimation Table and Diversity Factors Table (San Diego Gas & Electric Company, 2002)

2.5 CHAPTER SUMMARY

In the South African context, the SANS 507 standard makes provision for electrification design-planning requirements. In the standard, the fundamental and general planning concepts with regard to design planning are presented. The importance of the concept of load estimation is evident in all the standards presented as load estimation is the primary basis for electrification design planning. All the other standards be it Eskom or Municipality standards, they are all based on the SANS 507. The Municipal standards have been modified to suit the requirements of the specific supply authority within their area of jurisdiction. It is worth noting that the standard, nor the policies of the supply authorities do not rightfully so, explicitly provide guidance on the network topology to be implemented. The decision rests upon the designer / supply authority / developer.

In the international standards of the developed nations, the approach in terms of the guiding principles for electrification design planning are similar. Load estimation is still the basis for designing-planning in residential developments. A major beneficial point is in the load data collection of the supply authorities in order to provide more accurate load estimation models within their supply areas. A particular area of interest from the literature of the developed nations which is rightfully not in the specific national standard but in the supply authority standard is the network topology requirement. In all the supply authority standards, a clear guideline in terms of the design network topology requirements for electrification of residential developments in urban areas is indicated as underground networks. These supply authority standards provide various reasons for the adoption of underground networks within urban areas. These vary from mitigation of natural disasters (for nations prone to natural disasters), reliability and aesthetics amongst others.

Furthermore, it is important to note that both the local and international load estimation methods do cater for the design ADMD based on different social levels. Particularly the international supply authorities tend to have a design ADMD for a particular area or region. The resultant design ADMD is based on recorded load of the different regions over a period of time. In the local context, the SANS 507 ADMD tables are based on the collected consumer load data. The supply authorities then either adopt the SANS 507 tables or present their own design ADMD requirements either in line with the SANS 507 or above these requirements. A shortfall with some of the local authorities is the prevalence of a “blanket” design ADMD across their supply area. There is no differentiation of the different “regions” within the boundaries of their supply area. Both local and international supply authorities apply diversity correction factors applicable to their environment.

The international supply authorities have concentrated efforts with regard to the heating requirement as it a primary contributor to the design ADMD. One factor which the local context has not catered for is the residential electrical vehicle car charging. This is due to the fact that currently, electric vehicles have not been massively adopted yet within the local environment. Heading into the future, it is a factor worth considering and provision shall need to be considered perhaps for the higher LSM consumers.

A shortfall from both the local and international supply authorities is with regard to load estimation which caters for residential embedded generation. On all the literature presented, there is no guidance in terms of load estimation in areas where there are significant levels of residential embedded generation. Though outside the scope of this dissertation, load estimation for residential embedded generation and smart cities present significant future research potential.

It is therefore the objective of this dissertation to seek a balance, applicable to the particular context, in providing a sustainable evaluation model for residential developments which guides the residential electrification design topology. In the next chapter, a thorough investigation into the network design topology options shall be carried out.

CHAPTER 3

3. NETWORK TOPOLOGY INVESTIGATION

3.1 ELECTRIFICATION NETWORKS

A thorough analysis of the different electrification networks topologies is presented and investigated. The basis of the investigation shall be on the underground networks as a reference and compared to overhead networks. The design-planning-construction pros and cons shall be investigated with the high-level operation-maintenance components included. The approach for the topology investigation shall be through the breakdown of the network to major components / equipment making up the network. The hybrid network topology shall be primarily the selection of a combination of the best of both worlds. The combination of different overhead and underground network components shall result in a preferred network design topology for a particular application. The preference varies from application to application and is at the discretion of the designer or the supply authority design policies.

3.2 UNDERGROUND NETWORK TOPOLOGY

The service life cycle for a distribution network is limited by the service life of the equipment used in the distribution network. Cables and miniature substations are the main components in an underground distribution network. In this dissertation, the main components are described as the components in the event of their failure resulting in affecting n consumers which renders the network not fulfilling its design functions of serving n consumers. Depending on several factors including environmental conditions and loading factors amongst others literature prescribes a services life of approximately 30-40 years for underground electrical networks (Bumby *et al.*, 2010:5590). In the underground network topology, the following are the major components used in residential electrification:

- MV, LV & Service Connection Cables.
- Miniature Substations.
- Accessories (Service Distribution Kiosk, Joints & Terminations).

Each of these components shall be investigated in relation to their functionality with regard to their contribution in the underground network topology.

3.2.1 MV & LV Cables

MV electrical distribution is dominated by a combination of Paper Insulated Lead Covered (PILC) and Cross Linked Polyethylene (XLPE) power cables either in three-core or single-core configuration, for residential distribution the MV cables used are three-core configuration cables. These two types of cables are available in either Copper (Cu) or Aluminium (Al). Over the years due to theft associated with Cu cables and in areas classified as high-risk areas, most supply authorities have adopted Al equivalent cables in MV distribution instead of utilising Cu cables.

The initial PILC MV cable systems were developed in 1890 by Ferranti (Du Plessis, 2017:22). Globally, there has been a trend to move towards the “performance improved” XLPE cables from the 1970’s, whereas in South Africa, the trend started in the early 2000’s – this is predominately due to the costs associated with polymer manufacturing and the reduced skill set required for XLPE cables compared to PILC cables (Moore, 1997). The adoption of XLPE cables is mainly due to the ease of working the cable during installation and operations-maintenance stages. XLPE has superior mechanical and electrical properties in comparison to an equivalent size PILC cable.

In the 1980’s supply authorities started installing the first generation of XLPE cables. These XLPE cables had a poor operational reputation and service history associated with them primarily due to the following factors (McKenzie-Hoy, 2016:4):

- Inappropriate manufacturing techniques.
- Unacceptable testing methods.
 - DC pressure testing is a norm on PILC cables, this was also applied to XLPE cables prior energising the cables and / or during fault finding, but this only accelerated insulation failure.
 - This insulation failure is known as the water trees phenomenon – which is the chemical degradation of polymers in the presence of electrical stresses and water.

Thus, South African supply authorities have both PILC and XLPE installed in their distribution networks – in recent years, Eskom’s policy has been to install XLPE cable systems in Greenfields projects (new infrastructure projects) and continue with PILC installation for Brownfields projects (maintenance and / or existing network extensions).

The PILC cable technology is characterised by the following and complies with the specific requirements of SANS 97 – Electric Cables – Impregnated Paper-Insulated Metal-Sheathed Cables for Rated Voltages 3,3/3,3 kV to 19/33 kV:

- Paper is the primary insulation which is mass-impregnated with a non-draining compound – to avoid paper damage, the paper is helically applied with small gaps to allow for bending of the cable within the prescribed bending radius.
- These cables are highly susceptible to moisture – a detailed moisture testing procedure is of paramount importance.
- The continuous maximum conductor temperature is 70°C and maximum short-circuit conductor temperature is 160°C or 250°C (this is due to the soldering commencing to soften up at temperatures above 160°C, whereas if crimped connectors are used, the allowable maximum temperature is 250°C).
- Cable armouring is either Double Steel Tape Armour (DSTA) or Steel Wire Armour (SWA) – the SWA has lower impedance and has provision for higher mechanical forces during pulling of the cable.
- Belted cable construction or collectively and individually screened construction options are available.
- Cables are manufactured with flame retardant material – that is, once the flame source is removed, the material is self-extinguishing and the material will not support combustion.

The XLPE cable technology is characterised by the following and complies with the specific requirements of SANS 1339 – Electric Cables – Cross-Linked Polyethylene (XLPE) Insulated Cables for Rated Voltages 3,3/3,3 kV to 19/33 kV:

- An extruded polymer is the primary insulation which is either cured by a dry nitrogen process or cured by steam.
- These cables are triple extruded i.e. the core screen, XLPE insulation and conductor screen are extruded together – this results in air voids and moisture ingress being largely avoided.
- The continuous maximum conductor temperature is 90°C and maximum short-circuit conductor temperature is 250°C (for crimped connectors, the allowable maximum temperature is 250°C).
- Cable armouring is either DSTA or SWA – the SWA has lower impedance and has provision for higher mechanical forces during pulling of the cable.
- Cables are manufactured with flame retardant material.

LV electrical cables used in residential distribution networks are predominately 4-core Polyvinyl Chloride (PVC) cables and XLPE cables are hardly used in residential applications. These are also available in both Al and Cu.

The Polyvinyl Chloride Low Voltage (PVC LV) cable technology is characterised by the following and complies with the specific requirements of SANS 1507 – Electric Cables with Extruded Solid Dielectric Insulation for Fixed Installations (300/500 V to 1 900/3 300 V) – Part 3

- PVC is the primary insulation which is a polymer known as a thermoplastic.
- The continuous maximum conductor temperature is 70°C and maximum short-circuit conductor temperature is 160°C.
- Cable armouring is Galvanised Steel Wire Armour (GSWA).
- Cables are manufactured with flame retardant material.

Service connection cables are PVC and comply with the requirements of SANS 1507 – Electric Cables with Extruded Solid Dielectric Insulation for Fixed Installations (300/500 V to 1 900/3 300 V) – Part 6. These cables provide the final link between the supply authority and the consumer. The detailed design techniques for the cables are outside the scope of this dissertation and will not be discussed further.

3.2.1.1 Cable Derating Factors

In underground electrical distribution network design, the derating factors of the cables need to be taken into consideration. Cable derating is the phenomenon of operating electrical cables at a value less than its standard rated current carrying capacity size due to the surrounding installation environment. These factors are listed below and the associated derating factors are provided by the specific cable manufacturer based on the cable technology:

- Depth of Laying.
- Thermal Soil Resistivity.
- Laying in Cable Duct.
- Cable Spacing in Horizontal Formation.
- Ground Temperature.
- Air Temperature.
- Direct Solar Radiation.

These factors need to be taken into consideration in the design – it should be noted that there are standard practices which ensure that some of the derating factors are evaded in order to ensure that there is no derating for the particular factor. One of the standard practices is associated with the depth of laying the cable. MV and LV cables have optimal depths of laying which ensure that there is no derating for the cables in relation to the depth of laying.

Another standard practice is associated with the soil thermal resistivity of the bedding and blanket soil. The use of imported, properly specified soil thermal resistivity of the bedding and blanket soil ensures that there is no derating required for the cables due to efficient heat dissipation of the soil.

For the case of cable ducts, there is a minimum cable length which can be laid in cable ducts as a function of the cable duct outer diameter for the cable not to be derated. This relation was demonstrated by Vaucheret et al. (2005). For any cable laid in a cable duct in which the cable length through the cable duct is 20 times greater than the outer diameter of the cable duct, then the cable shall be derated (Vaucheret *et al.*, 2005:563). The other factors are either out of the designers control or are uneconomical to comply with, thus the designer shall need to derate the cable for the particular application of the cable.

3.2.2 Miniature Substations

In residential distribution, transformation from the medium voltage level to the low voltage level utilised by the consumer is required. In underground residential distribution, this function is carried by the miniature substation – this is a component which in most cases consists of three compartments, namely, the MV compartment, transformer compartment and LV compartment. The miniature substations comply with the requirements of SANS 1029: Miniature Substations for Rated AC Voltages up to and including 24 kV.

The economic useful service life of a miniature substation is assumed as 30 years. The MV compartment accommodates the MV switchgear which consists of two incoming and outgoing MV feeders with a local MV switch for the MV terminals of the transformer. The MV switchgear is required to comply with the requirements of SANS 1874 Switchgear – Metal-Enclosed Ring Main Units for Rated AC Voltages above 1 kV and up to and including 36 kV.

The local transformer MV switchgear can either be a circuit breaker or a fuse – this is dependent on the supply authority's requirements. The MV switchgear is provided with four insulation medium options, namely: oil, Sulphur Hexafluoride (SF6) gas, vacuum or air. Most supply authorities have leaned towards the SF6 gas and vacuum MV switchgear due to the reduced maintenance requirement associated with these two types of insulation medium compared to the oil filled switchgear.

The transformer compartment accommodates the transformer, these transformers comply with the requirements of SANS 780 – Distribution Transformers. Most distribution transformers installed inside miniature substations within the South African residential distribution networks are predominately oil-filled transformers.

In recent years, there has been a rise in the adoption of dry type transformers by supply authorities due to the lessened maintenance requirements in comparison with oil-filled transformers.

3.2.3 Accessories (Service Distribution Kiosk, Cable Joints & Terminations)

Service distribution kiosks serve as the LV distribution point to the consumer. These are LV switchgear enclosures which accommodate the LV network switchgear and meters. Service distribution kiosks are manufactured from either steel or fibre glass. This is dependent on the supply authority's requirements. In recent years, in order to minimise the risks associated with infrastructure vandalism and illegal connections, supply authorities' have continuously revised the requirements of the service distribution kiosks. This includes the kiosks designated as high risk which make provision for extra protection mechanisms in areas which are considered high risk by the supply authority.

In the electrical distribution environment, cable joints and terminations are considered the weakest elements in the distribution network as these are the components which have a high failure rate (Steennis *et al.*, 2011). The detailed investigations on the causes of failure in these components is beyond the scope of this dissertation. In recent years, work has been continuously performed to develop and ensure a higher level of reliability is attained from these components.

3.3 OVERHEAD NETWORK TOPOLOGY

In the overhead network distribution topology, the main components are the conductors, poles and transformers. In this dissertation, the main components are described as the components in the event of their failure resulting in the affecting n customers which renders the network not fulfilling its design functions of serving the n customers. Several authors have performed extensive work on estimating the service life of an overhead distribution networks and these vary between 40-50 years (Bumby *et al.*, 2010:5590). In an overhead distribution network, the following items are the major components used in residential electrification:

- MV & LV Conductors.
- Concentric Service Connection Cable.
- Poles (Concrete or Wooden).
- Pole Mounted Transformers.
- Accessories (Pole Top Boxes, Joints & Terminations).

3.3.1 MV & LV Conductors

In residential overhead MV distribution, primarily Aluminium Conductor Steel Reinforced (ACSR) conductors are used due to their mechanical strength and current carrying capacity. For coastal areas, greased ACSR conductors are used in order to minimise the effects of corrosion. The mechanical strength provided by the galvanised steel reinforcement make it possible for variable economical span lengths and to have sufficient statutory clearances required in residential areas. These overhead MV conductors comply with the requirements set out in the SANS 182-3 – Conductors for Overhead Electrical Transmission Lines – Part III (Aluminium Conductors Steel Reinforced). Overhead MV conductors are characterised by the following:

- Mechanical properties – tensile strength.
- Operating conditions – ranges from 50°C to 80°C.

At the peak of the National Electrification Program, insulated overhead bundle conductor, namely Medium Voltage Aerial Bundle Conductor (MV ABC) was used extensively. The conductor is still in use in some supply authorities' networks, the shortcoming with the MV ABC was caused by insulation wear over time, resulting in an increased risk of conductor flashovers i.e. the electrical discharge through weakened insulation between live conductors in close proximity. The MV bundle conductor is designed according to the requirements of SANS 1713. The overhead conductor of choice within LV networks is the Low Voltage Aerial Bundle Conductor (LV ABC). This conductor consists of stranded aluminium conductors with an XLPE based insulation which ensures ultra-violet rays protection.

The LV ABC conductor complies with the requirements of the SANS 1418. These conductors are either self-supporting or consist of a supporting core. The LV bundle conductor has a wide operating range from -50°C to 80°C. In the older suburban areas within most Metropolitan areas, the bare overhead LV conductors used are the All Aluminium Alloy Conductor (AAAC). These were mainly used due to the shorter span length requirement of the LV networks and the aluminium alloy provides sufficient strength required for these relatively shorter span lengths. In recent years, supply authorities have moved away from bare overhead conductors and moved towards overhead ABC mainly to promote public safety as the conductor is completely insulated. This has predominately been driven by the costs and the mass production of LV ABC through industry adoption as the preferred overhead LV network conductor. The clearance requirements for insulated conductors are fairly more relaxed than bare conductors.

3.3.2 Poles (Concrete, Wood or Steel)

In residential overhead MV and LV networks, both concrete and wooden poles are used as support structures for overhead conductors. In most metropolitan areas, the supply authorities have adopted the use of concrete poles over wooden poles mainly to curb the vandalism of the electrical infrastructure.

Wooden poles are still in use and predominately used in small urban areas / townships where vandalism is not so prevalent in comparison to metropolitan areas. There are instances in some old urban areas within the inland areas in which galvanised steel poles were used. This practice has ceased and galvanised steel poles are predominately used for street lighting purposes.

Concrete poles are characterised by their high mechanical strength. They are not prone to vandalism and require less maintenance in comparison to wooden poles. Concrete poles comply with the requirements set out in the SANS 470. Concrete poles are prone to being conductive to lightning in comparison to wooden poles, recent developments include the inclusion of earthing bars within the concrete structure for earthing purposes. Wooden poles used in electricity distribution are required to comply with the requirements of the SANS 754 and SANS 753 respectively.

Wooden poles if properly maintained can result in a considerably longer life-span. They are also exposed to lightning strikes and veld fires, even though they are treated with fire retardant materials (Geldenhuys & Stanford, 2006). Basic insulation level techniques for MV lines with air gaps are utilised to minimise the effects of lightning strikes for both wooden and concrete poles. Basic insulation level is the bonding of MV lines in order to ensure that the lines are safe, have a lower probability of failure and reduced failure rate.

3.3.3 Pole Mounted Transformers

Pole mounted transformer comply with the requirements of SANS 780 – Distribution Transformers. The sizes of the transformers used in residential reticulation vary from 100kVA to 315kVA depending on the supply authorities' standards and policies. These transformers are accommodated by suitably sized pole structures. Most distribution transformers installed on the South African residential distribution networks are predominately oil-filled transformers. The main drawback of these transformers is the prevalence of oil-leaks in the event that maintenance is not carried out on these units.

3.3.4 Accessories (Pole Top Boxes, Conductor Joints, Connectors & Terminations)

In overhead residential electrification, fibre glass pole top boxes and steel pole mounted service distribution boxes are used. The high-risk security steel pole mounted boxes are predominately used in “high-risk” areas to alleviate vandalism and illegal service connections. In overhead networks, the terminations and the joints are susceptible to failure due to exposure to the extreme of environmental conditions. In the overhead topology context, all the equipment is mostly exposed to the extreme environmental conditions of wind, moisture, sunshine, both high and low ambient temperatures.

3.4 HYBRID NETWORK TOPOLOGY

The hybrid network topology is the combination of the underground and overhead networks. The most prevalent configuration is the medium voltage network being underground and the low voltage network being overhead. There are different permutations applicable which are mainly subject to the supply authority’s needs and requirements.

3.5 COMPARISON OF THE UNDERGROUND AND OVERHEAD TOPOLOGY

Without any doubt, there is a suitable and justifiable application for either of the network topologies within residential electrification. In this section a detailed comparison for each of the major components shall be undertaken. In performing the comparison, the prevalent conditions shall be assumed to be neutral and suitable for the implementation of both topologies i.e. the conditions shall not be such that, a condition results in a more favourable case for any of the two topologies.

3.5.1 Cost of Underground versus Overhead

Several cases were presented in Chapter 1 of this dissertation in which the cost evaluation associated with the conversion of existing overhead infrastructure to underground residential network has been undertaken. In order to perform a fair and just evaluation of electrical infrastructure comparison, the equivalent network design topology on the same technical design criteria has to be performed, i.e. the designs to be compared need to be at the same ADMD.

Most supply authorities have different design level criteria depending on the type of residential development and classification. The metropolitan supply authorities tend to have a fixed design ADMD as indicated in Chapter 2 across the residential development types. The case is a bit different with regard to smaller supply authorities which tend to have different and lower design criteria – these supply authorities normally rely on the guidelines as issued by Eskom and the national standard, the SANS 507.

For most of the non-metropolitan sized towns, the design criteria in terms of the ADMD varies from 1.5kVA to 2kVA. In metropolitan areas the design ADMD varies from 3kVA to 5kVA depending on the supply authority and the indicated LSM within the particular residential development. Design criteria greater than 5kVA is predominately used in the up-market residential development infrastructure segment and this is normally assessed on a case by case by the specific supply authority. It must be noted that, in the up-market residential segment, residential network electrification has over the years been a “non-negotiable” and is implemented strictly using the underground network topology predominately due to the less desirable low aesthetic component associated with overhead electrification networks.

An additional factor is due to the high load density within these types of residential developments, this results in mass produced overhead pole mounted transformers (maximum capacity size 315kVA) being the primary constraint due to the high load requirement per unit area. Overhead network design topology in these instances seem economically unfeasible. In South Africa, the up-market residential electrification segment is a relatively small component in terms of numbers in comparison with the middle-market and lower-market segments.

In the lower-market segment, the design criteria ADMD range is 1.5kVA to 2kVA, as a result, residential electrification is predominately designed on overhead residential networks for this market segment. This is primarily due to the lower capital cost of the overhead networks in comparison to underground networks and a lower load density. The low voltage network shall not be optimised on an underground system as a larger number of consumers can be theoretically supplied from the smallest capacity mass production miniature substation (315kVA), but the feeder distance would be longer. In addition to that, the smallest mass production miniature substation would then not be optimally utilised as it would be loaded to a much lower loading. In this particular case the LV network shall not be feasible due to long LV network feeder lengths.

On the basis of the above, the middle-market segment is one which presents economically viable different network design topology options. This segment is the major market dominator as most of the mega residential development projects are within this market segment. Mega residential development projects are government driven housing projects ran by the Department of Human Settlements. These projects are defined as accelerated residential infrastructure delivery projects and have a minimum of 10 000 residential units. These types of projects were the main driver which resulted in formulation of this research dissertation.

For the remainder of the dissertation, the lower-market design topology shall be accepted as fulfilling design criteria requirements through the implementation of overhead network design topology.

The up-market segment design topology shall be accepted as fulfilling design criteria requirements through the implementation of underground network design topology. The table below provides the design ADMD and the average capital cost comparison across different supply authorities for the different electrification network topologies. The electrification network topologies covered are overhead, underground and hybrid networks for single residential units (low density units / single stands). The average costs are sourced from a combination of recently completed projects in the middle-market segment.

Design ADMD	Cost per Unit		
	Underground Topology	Overhead Topology	Hybrid Topology
3.5	R 24 500	R 19 500	R 21 000
5	R 31 000	R 23 500	R 26 250

Table 3-1: Residential Network Topology Typical Cost per Unit.

To date, there is no proper documented literature and readily accessible data on the operational costs of the different network topologies within the borders of the country. This is due to the fact that there is no proper record of all the maintenance activities carried out on the different network topologies. A proposed method for the estimation of operational costs based on documented literature shall be presented in Chapter 4.

3.5.2 Cables versus Overhead Conductors

In residential developments, the available land mass for services is within the road reserve. In the road reserve there are several other services amongst others, water, sewer, storm-water and telecommunications. In urban areas, it must be noted that, real estate is at a premium and thus there is not a lot of free will manoeuvring available for installing services within the road reserve.

3.5.2.1 Medium Voltage Network

MV feeders from the distribution substation are spread across the development area to supply power at the required load centre points. A typical development consists of approximately 10 000 residential units as a combination of high density units and low density single residential units.

With the assumption that the load requirement is 50MVA, the MV network shall need to transfer the load requirement from the distribution substation to the residential development. Most supply authorities use standard underground cables and / or overhead conductors in accordance with the current carrying capacity of the particular cable and / or overhead conductor.

That is, the standard underground cables and / or overhead conductors used are based on the design load which can be accommodated by the network. For instance, the supply authorities require MV ring networks with a maximum installed transformer capacity of 6MVA to 7MVA including an (N-1) state. This means the maximum MV configuration capacity is able to accommodate the load within the ring in the event of failure of a portion of the ring. Provision for possible future load growth and densification where applicable is as standard practice taken into consideration.

3.5.2.1.1 Cable Network

For underground reticulation, suitable sized cables and in accordance with the supply authorities design standards and policies are utilised. This correspondence with the following MV cable sizes, maximum capacity and ring networks required to supply the development.

Cable Size	Material	Insulation	Capacity (@11kV)	Number of Ring Networks Required
300mm ²	Al	XLPE	420A – 8.00MVA	7
185mm ²	Cu		410A – 7.81MVA	7
300mm ²	Al	PILC	340A – 6.48MVA	8
185mm ²	Cu		335A – 6.38MVA	8

Table 3-2: Residential Development Cable Network Requirements.

3.5.2.1.2 Overhead Conductor Network

For overhead network reticulation, suitable sized overhead conductors and in accordance with the supply authorities design standards and policies are required. This correspondence with the following MV conductor name, maximum capacity and ring networks required:

Conductor Name	Material	Capacity (@11kV)	Number of Ring Networks Required
Hare	ACSR	360A – 6.86MVA	8
Wolf		470A – 8.95MVA	6

Table 3-3: Residential Development Overhead Network Requirements.

Since the major constraint within these developments is the real estate itself, in terms of the load requirement, the minimum number of ring networks required for the overhead and underground networks are six (6) and seven (7) MV rings respectively. This results in a minimum of twelve (12) outgoing feeders and six (6) stand-by feeders which equates to eighteen (18) feeders required from the substation.

In terms of the distribution substation footprint, with an ideal substation located towards the load centre point of the development, ideally there shall be a minimum of four main directions available for the MV feeders to be distributed within the development.

In case of overhead conductors, due to the pole structures required, it is a bit challenging to distribute MV overhead conductors consisting of more than eight (8) feeders from a distribution substation within a residential development in an urban environment. The assumption for eight (8) feeders is achieved by having two feeders in each of the four main directions.

3.5.2.2 Low Voltage Network

The primary constraint in LV network feeder design is the voltage drop which is associated with the length of the LV network feeder. Thus, it is not only the load requirement that is critical. The load is provided by the number of domestic consumers supplied from an LV feeder. The combination of these two factors (voltage drop and the load) are considered in order to ensure that adequately sized protection devices are implemented in the LV network. The LV network design is in a radial configuration for operational purposes and economic considerations. Redundancy in residential networks is catered for in the MV network and it is not catered for in the LV network. Network faults in the LV networks are relatively easier to resolve, with a relatively few number of consumers affected in comparison to the network faults in MV networks.

3.5.2.2.1 Cable Network

In underground residential electrification LV networks, 4 core PVC insulated cables are predominately used. The type of cable utilised in a residential network is as per supply authority's requirements and policies. These are supply authority specific with some having a preference for Cu cables while others have adopted Al cables. The cable sizes varies between 70mm² to 185mm² with the combination of the load requirement and feeder length used as a determining factor.

3.5.2.2.2 Overhead Conductor Network

In overhead residential LV network, LV ABC conductor is widely used across the board by all the supply authorities. This ranges from predominately the light weight 70mm² to heavyweight 120mm² LV ABC conductor. The use of the heavy conductors' results in more consumers being supplied but at the same time the span length shall be required to be relatively shorter in comparison with the lighter conductor. These trade-offs are design specific and are normally to the discretion of the designer unless it is a supply authority standard and policy to only use a specific sized overhead conductor.

3.5.2.3 Service Connections Network

The service connection network is the final interface between the supply authority and the domestic consumer. In an attempt to alleviate the prevalent effects of non-technical losses, split metering is used by most supply authorities. This requires communication between the consumer interface and the domestic meter. This is achieved either by additional communication cores on the service connection cable or with the implementation of powerline communication i.e. the applications of live conductor cores for communication.

3.5.2.3.1 Cable Network

The use of either 2-core or 4-core service connection cables for domestic consumers to meet the consumer supply requirements either in single or three-phase configuration. The cables are installed at a depth which ensures there is no cable derating, with a suitably bedded and blanketed soil which does not derate the cable as well.

3.5.2.3.2 Overhead Conductor Network

The overhead service connection component is achieved with the implementation of an overhead concentric service connection cable. In some instances where the span length from the LV network infrastructure is greater than 20m or service connection passes over the road, an additional pole (kicker-pole) is required for support purposes and to comply with the statutory regulatory clearances.

3.5.3 Transformers and Miniature Substations

In overhead network reticulation the pole mounted transformers are primary constrained by the strength of the poles which are used as a base for the transformer. The transformer capacity is proportional to the physical size and dimensions of the transformer. In residential electrification the maximum capacity pole mounted transformer used is 315kVA. The number of consumers serviced by the transformer is thus dependant on the design load requirement – ADMD.

Miniature substations are used in underground residential electrification with a transformer sizing up to 800kVA being used by some supply authorities for residential application. Due to the larger available transformer capacity, a significantly large number of consumers are serviced by the single miniature substation in comparison to a pole mounted transformer. In short, the service density and supply area of miniature substations is more than that of the pole mounted transformers. Due to the mass production of the miniature substations, there is not a significant sizing difference in terms of dimensions between the 315kVA to the 800kVA transformers which are predominately used in residential applications.

3.5.4 Social and Environmental Factors for Underground and Overhead Network Topology

A benefit analysis will focus more on the social and environmental factors prescribed by the different topologies. In residential electrification, as real estate is prime, underground cables tend to be an economically viable option in comparison with overhead conductors which require a lot more real estate due to the load density within residential developments. It is fair to say that, irrespective of which topology being implemented, the technical requirements need to be fulfilled.

The social benefits are arguably difficult to estimate and quantify but shall be presented. The quantification of these benefits falls outside the scope of this dissertation and can be considered as future research work which can be undertaken. In underground residential reticulation there is definitely a more aesthetically pleasing and “easy-on-the-eye” feeling in terms of the electrical infrastructure in comparison with overhead residential reticulation. The equipment in underground reticulation which are above ground are miniature substations and service distribution kiosks, whereas in overhead reticulation it will be the overhead conductors, poles and buggy pole mounted transformers.

The aesthetics bring about an indirect value in terms of real estate appreciation within the development, coupled to this are the social attributes of the people within such an environment (Pelegrini *et al.*, 2011). The contributing social factor perceived by the underground reticulation is the safety and quality of supply improvements associated with the network topology in comparison with overhead networks.

The feeling of safety associated with underground networks is much higher in comparison with an objective view of observing bare overhead conductors and poles in relation with an underground system where a significant less number of equipment is observed by an objective person. In underground reticulation, there are less environmental disturbances in terms of tree felling which in most cases provides a habitat within the ecosystem for a number of creatures.

3.5.5 Benefit Analysis of Underground and Overhead Network Topology

The table below provides a comparative summary for underground and overhead residential electrification topologies.

Factor	Underground	Overhead
Public Safety	Cables are installed underground, with little chance of public hazard	Bare overhead conductors installed along poles and visible to the public – presents a chance of public hazard
Initial Costs	Underground cable installation network is more expensive than the overhead network	Overhead network is less expensive in comparison to an underground network
Operational Costs	Underground network costs are comparatively lower to overhead system as there are less chances of faults, service interruptions even though faults might take longer to rectify if they occur. Anomalies in costs are normally prevalent in instances where there is an installation of other services within the vicinity of cable	Overhead network has comparatively higher costs even though conductors are visible, accessible hence fault locations are easily identifiable, the main drawback is the frequency of the faults and service interruptions. This is primarily due to trees, lighting and wind
Useful Design Life	30-40 years	40-50 years

Factor	Underground	Overhead
Aesthetics	Aesthetically pleasing, socially and environmentally friendly	Not easy on the eye, prone to lightning strikes and trees within the path need to be regularly cut to ensure no interference with the open conductors
Current Carrying Capacity	Underground cables providing the same current carrying capacity require a larger cross-sectional area than overhead conductors	Overhead conductors have a higher current carrying capacity for the same sized underground cable cross sectional area
Loading	Underground systems cannot handle overloading, overloaded cables tend to result in increased faults due to insulation failure	Overhead conductors can handle overloading conditions much better than underground systems
Impedance	Underground cables have a lower voltage drop for the same length circuit due to lower impedance	Overhead conductors have a higher impedance thus resulting in a large volt drop for an equivalent circuit due to higher impedance
Electromagnetic Interference	Underground cables do not provide any electromagnetic interference with communication lines	Overhead conductors are relatively prone to cause interference with overhead communication lines than underground systems – communication system have over the years adopted fibre as a primary medium, hence the interference problem has diminished

Factor	Underground	Overhead
Flexibility	Underground system is more rigid in comparison to the overhead system as trenching is required in order to access the cable and it is highly likely there will be other services in close vicinity of the cable	Overhead systems are much more flexible, upgrades on overhead lines are much more achievable than on underground systems
Reliability	Underground cables have proven to be more reliable than overhead lines, even though they might have longer fault repair / identification duration	Overhead lines are less reliable primarily due to the frequency of faults and service interruptions even though the fault repair / identification duration is much shorter than underground networks

Table 3-4: Comparative Summary of Underground and Overhead Network Topologies

3.6 STATUS QUO IN RESIDENTIAL ELECTRIFICATION NETWORK DESIGN TOPOLOGY

The current approach applied by both supply authorities and developers in the design-planning for residential electrification is currently vaguely flexible in terms of which network topology is to be implemented in the middle-market segment. Projects are treated on an ad-hoc basis with no systematic process in deciding which network topology to be implemented. Based on previous experiences with some of the supply authorities, a decision on the network topology is based on “gut-feel” at the design-planning forum / committee of the supply authority. In some instances, the supply authority, base the decision of the network topology on existing infrastructure in the neighbourhoods close to the proposed development. This more often than not leads to shortcomings in terms of long term sustainable network infrastructure in residential developments.

There is currently an oversight on the sustainability of the network infrastructure as we are in a dynamic environment which is continuously changing at a significant rate. Long term network infrastructure decisions need to be rationalised and based on a systematic approach.

The current shortcomings are not necessarily in the design-planning stage, but this stage is critical in the long-term view of sustainable network infrastructure. A holistic view in terms of the network infrastructure costs needs to be considered and not only the short-term objective. The current trend which is implemented by most supply authorities is in the significant purposeful over-design for residential electrification networks which is meant to compensate for the lack of maintenance on the residential networks. This is a double-edged sword in the sense that due to maintenance not being performed, a significantly less number of new residential electrical infrastructure is installed to service new residential housing opportunities. This is mainly due to that fact that limited funding is available to cater for a given number of residential housing opportunities. In the perspective of the supply authorities, the overcompensation of the network in the design-planning stage enables and makes provision for an extended window for networks which “do not” require maintenance.

Supply authorities, which are licensed electricity distributors are regulated by NERSA, they are required to provide annual reporting to the regulator on an annual basis on the performance of the network. This is part of the licensing requirement in which the average duration and frequency of interruptions are reported. A shortcoming which is not properly recorded by the supply authorities which is not regulated is the maintenance carried in the networks. A proper record of this is critical as it would enable the supply authority to know with a high degree of certainty the budgetary requirement associated with network maintenance. As things stand, maintenance on electrification networks is mostly performed as corrective maintenance after network failure and / or breakdown which is the most expensive of the maintenance schemes. It is mostly corrective maintenance, preventative maintenance hardly exists and in most cases, there is no maintenance at all.

A challenge encountered by most supply authorities is associated with non-technical losses experienced within the networks. This is largely due to illegal connections in most residential areas and there are random cases in which there are illegal connection in non-residential areas. In addition to this, it is the vandalism and stealing of electrical conductors which are in turn sold in the scrap metal industry. The cost losses experienced by supply authorities due to these non-technical losses is of large magnitude. This has a negative effect on the revenue collection for the supply authorities.

A detrimental challenge is encountered mostly in small supply authorities which do not have proper revenue collection mechanism in place. Case in point will be such, a small supply authority purchasing electricity from Eskom to distribute within its licensed distribution area. These small supply authorities more often than not do not have proper billing systems to collect revenue.

Eskom being the seller, implements electricity sales using time-of-use tariff but the small supply authority does not necessarily have time of use tariffs applied or used as a revenue collection mean (smart metering) within their network. This result in a shortfall in terms of revenue collection and the payment due to Eskom.

Furthermore, with revenue collection, as most licensed supply authorities are either a municipal entity or they are a municipal department within the municipality. The revenue collected from electricity sales is normally not ring fenced to electrical infrastructure services, but it cross subsidises some other functions of the municipality. This results in critical electrical infrastructure services being short cut and services not rendered, like maintenance.

The supply authorities have another obstacle in terms of the financing of capital projects, the flow of money normally flows from national, province and then municipal sphere of government. The equitable share available at municipal level is not large enough to enable implementation of capital projects from the supply authority budgets. Capital projects are normally financed through the Department of Energy Integrated National Electrification Programme (INEP) or the Urban Settlement Development Grant (USDG) for metropolitan municipalities. Supply authorities are more often than not exposed to finance which is from external sources in which developers fund the design-planning and construction in line with the supply authority requirements and / or policies associated with the infrastructure. The infrastructure is then handed over to the local authority on completion of the construction stage.

The supply authorities described above, additionally experience political directives in which technical services are not necessarily performed but politics are being managed. This in turn has led to a large exodus of skilled personnel within these supply authorities primarily due to political directives. In such instances, it plays a big role if the technical person which interacts with the political heads is a strong character with an understanding of managing working relations with different people.

3.7 CHAPTER SUMMARY

In this chapter, a thorough investigation into the different network design topologies was presented. It was demonstrated in this chapter that, there is a fair opportunity for providing a combination of sustainable infrastructure solutions within the middle-market segment.

It was further affirmed in this chapter that, the lower-market segment is ideally suited being serviced by overhead network topology whereas, the up-market segment is catered by an underground network topology. It is fair to say, the middle-market segment consists of options which need to be assessed for economic feasibility and social contributions.

The next chapter will seek to provide an evaluation model which address the specific challenges in deciding which residential electrification design topology is most suitable for implementation.

CHAPTER 4

4. EVALUATION MODEL

4.1 INTRODUCTION

A detailed investigation on the different available network topologies was provided in the previous chapter with a brief overview of the status quo within the industry. Prior to providing the detail of the proposed evaluation model, this introductory section will demonstrate things which might go wrong in the event of implementing the least feasible network topology. For the scenario in which there has been an over-design of the electrification network irrespective of the network topology implemented, the conclusions as provided in Section 2.2.3 in Chapter 2 of this dissertation will become a reality. In the event of the inverse, in which a network has been under-designed in order to save initial capital costs, the network will end up being constrained in the medium to long term resulting in additional expenditure on the network. In cases whereby there are financial constraints, the golden rule is to ensure that, whichever short-term solution is being applied, it has to form part of the long-term objective. In this way, ad-hoc unnecessary expenditure is reduced, as all actions form part of the long-term objective.

Most decisions on the network topology are more often than not based on the initial capital costs, the capital cost factor does not necessarily provide a full assessment of the most suitable network topology to be implemented. The life cycle costs provide a much more fair and comprehensible base for cost comparison. In the event that the exercise of life cycle costing is not performed, a network topology might seem favourable in the short to medium term but totally expensive in the medium to long term. This will further result in a financial burden on the operations stage of the network infrastructure.

Consider an event in which, an overhead network is in operation and after a number of years prior the end of life of the network, an underground network is required due to prevalent reasons at the time in question. A costly decision, with a cost-benefit analysis shall have to be made with respect to how to proceed, either let the network remain as is with its perks or converting the network to an underground or hybrid network topology. In the literature review of Chapter 1 of this dissertation, the magnitude in terms of network topology costs conversion were presented. It is on that basis that the network topology alternatives need to be properly evaluated in order to receive the maximum benefit from the proposed network topology.

The social benefits which can be lost in network topology selection are not easily quantifiable, but the effects can result in either extremities. These social benefits brought about by network topology can have an effect on residential house prices and perceived public safety. These benefits require to be properly investigated in order to have accurate and substantiated effect based on the different network topology. There is a tremendous scope for future research work on this field.

In this chapter, the evaluation model is presented. The model is based on the AHP which is a pair-wise comparison method for multi-criteria decision-making. The framework of the model is on several factors presented in this dissertation and these shall be evaluated to provide a ranking of the most suitable design topology option based on the supply authority and / or developer preferences, choices and requirements. The model priority is to first fulfil the development load requirement and from there evaluate the different available network topologies which are suitable for the load requirement. The evaluation model is graphically represented below:

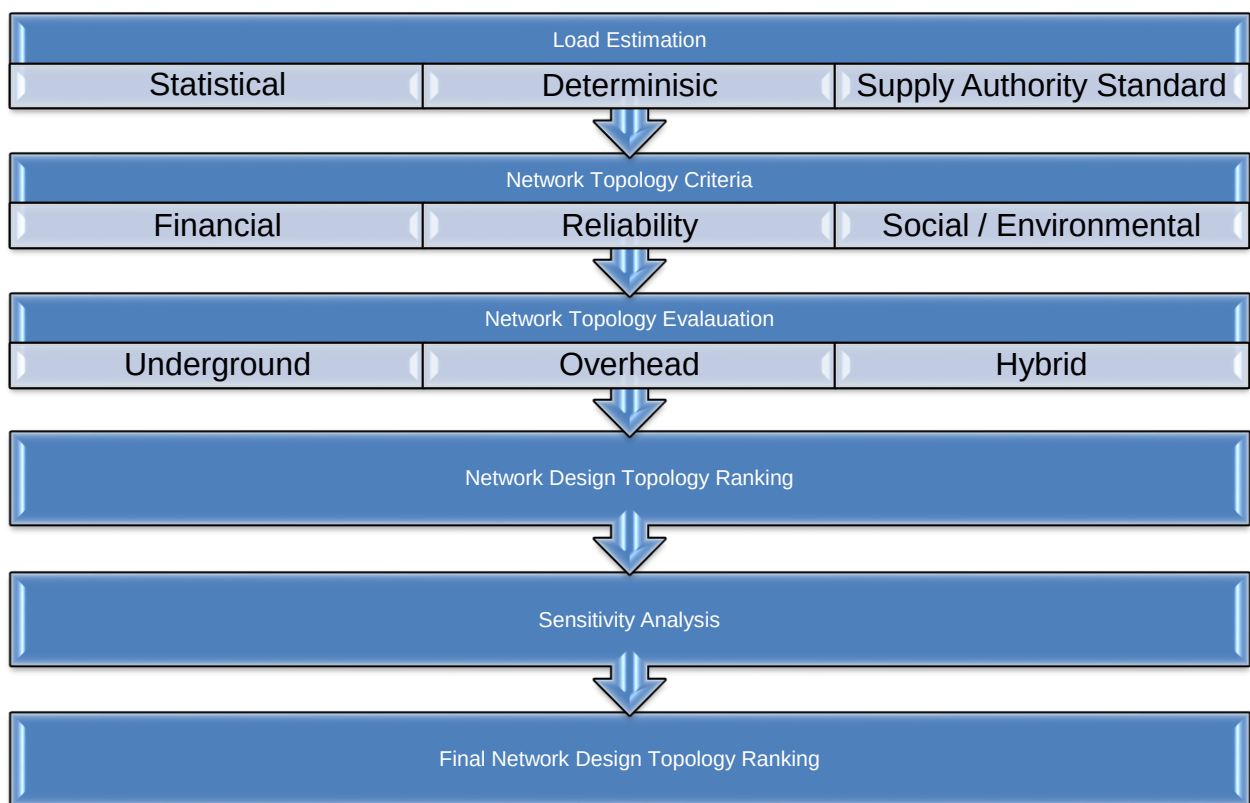


Figure 4-1: Electrification Network Design Topology Framework

4.2 EVALUATION MODEL FACTORS

The evaluation model is based on the development load requirement as the primary input. This shall need to be appropriately calculated to ensure that the development long term load requirements are fulfilled. The load requirement shall not form part of the criteria, but it will be a parameter which is used to establish the criteria for the different network topology options. The entire evaluation model is based on the fulfilment of the load requirement. Furthermore, the evaluation model primarily consists of two primary components, namely;

- Primary Input.
- Evaluation Criteria.

The primary input consists of fixed parameters, these are in turn implemented together with the evaluation criteria. The sections below shall detail how the respective components combined together shall provide an evaluation model which ranks electrical network design topologies.

4.2.1 Load Estimation – ADMD

Domestic load estimation is a specialised research area which has been undertaken in literature for a period of years as detailed in Chapter 2 of this dissertation. Essentially there are two approaches which are implemented for load estimation, this is namely;

- Statistical approach.
- Deterministic approach.

As this shall be the primary input of the evaluation model and the basis of the entire evaluation model, it is of paramount importance that this input is properly determined. The user can compare the preferred load estimation method results with the national minimum standard. The statistical approach is dependent on the availability of analysed historical domestic load research data. The statistical parameters, namely the α and β , shall be applied to perform the load estimation which will be the input to determine the end state ADMD for the particular development. In the case where the deterministic approach is preferred, using the Association of Municipal Electricity Utilities (AMEU) diversity correction factor, the resultant ADMD shall be input to the model. Both these methods require insight from first principles in order to attain the required results of the ADMD.

More often than not, the supply authorities shall have defined load estimation policies and standards which shall need to be compiled with. The evaluation model shall still be applicable in this instance, as the supply authority standard ADMD shall be input to the evaluation model.

The ability for the user to compare the input ADMD with the national standard is critical as it shall from the onset indicate how the calculated / defined ADMD compares with the national standard. Thus, an intuitive conclusion can be substantiated on why a particular ADMD is used. It is worth noting that, the infrastructure shall be an asset of the supply authority in most cases, thus the supply authority shall have an inherent interest on the ADMD design level requirement.

4.2.2 Evaluation Criteria

The different network topologies shall be evaluated on the different criteria and compared against one another. It is important to note that the comparison will be subjective but will seek to establish a consistent balance between the available criteria. The evaluation criteria shall be kept to a maximum number of three which covers the most important aspects. The main drive for the selected number of criteria is to ensure a simplified practical implementation of the evaluation model and not to unnecessarily overload / underload the information requirement to achieve a sustainable decision in electrical network design topology. The justification of each criteria in the model is detailed in the next sections.

4.2.2.1 Financial

Most decisions are taken solely based on the financial ramifications as the financial feasibility is more often than not the determining factor. The financial costing of the different topologies is based on actual costing of previous electrification projects with similar parameters. The financial evaluation for the different options makes provision for the holistic costing of the network design topology. These shall be the initial capital cost and the operational costs which when combined provide the life cycle cost of the different network design topologies.

4.2.2.1.1 Capital Cost

A direct comparison of the financial cost for the different network topology options shall be undertaken with actual previous electrification costing. The base comparison shall be an underground topology with these costs being compared to both overhead and hybrid network topologies. The capital costs are defined as all the costs associated with the design-planning and construction stages for a development. These costs are essentially the input from the user from previous similar completed residential electrification projects costing. The previous similar completed projects are defined as electrification projects which are characterised by having the same items listed below:

- Design ADMD.
- Design network topology (Overhead, Underground, Hybrid**).

*** Note: The hybrid network topology needs to be specifically quantified as there are a number of permutations which can be implemented, these are indicated as follows:*

- *MV underground: LV overhead.*
- *MV overhead: LV underground.*

The emphasis in applying the proper comparison for the different network design topologies is to ensure that a consistent comparison is performed. In the evaluation model, the parameter which ensures comparison consistency is the design ADMD. This is critical as this will provide consistent results as the comparison will be performed properly, that is, apples will be compared with apples.

4.2.2.1.2 Life Cycle Costing

Life cycle costing is per definition all the cost incurred during the economic lifetime of an asset, in this case, the electrical network. This is summarised as the sum of the initial costs, operational costs and decommissioning costs. There is not a lot of literature which covers the aspect of the operational costs in electrical networks over their life span. The evaluation model shall thus intuitively make provision for the operational costs of the electrical network over the economic lifetime as percentage of the capital costs.

The percentage shall be applicable for each of the different network design topology alternatives. Literature dictates that due to various methods in which operational costs are recorded, it is reasonable to set the annual operational costs as a functional of the initial capital costs. The set range set for the annual operational cost for electrical networks ranges between 1/30 (3.33%) to 1/8 (12.5%) (Willis, 2004c:24). In the evaluation model, this shall be user defined for the different network topologies as follows:

- | | | |
|-----------------------|---|---|
| • Underground network | – | 3.33% to 6.25% of initial capital cost. |
| | – | Average of 4.79% of initial capital cost. |
| • Hybrid network | – | 5.56% to 10.0% of initial capital cost. |
| | – | Average of 7.78% of initial capital cost. |
| • Overhead network | – | 7.14% to 12.5% of initial capital cost. |
| | – | Average of 9.82% of initial capital cost. |

These costs are assumed to commence from the beginning of year 2 of the electrical infrastructure. Year 0 is the year the infrastructure is installed and commissioned, whereas year 1 is covered in terms of the 12-month defect liability period from the date of completion of the works.

In the evaluation model the infrastructure life cycle cost analysis is carried over a period of 20 years, with the annual operational costs taken over a period of 18 years commencing from year 2.

4.2.2.2 Reliability

The case of reliability is essential in electrical networks as revenue is generated on a functional network. If the network is not functional, revenue is lost. A comparison of the different topologies in relation to one another shall be made. The energy regulator in the country compels the electrical energy distributors to provide yearly reports on the reliability of their electrical network infrastructure. These are reported as the SAIDI & SAIFI indices by the supply authorities on a yearly basis. These indices indicate the yearly system interruption statistics within the licensed distributors supply boundaries. The “system” which is essentially the entire electrical distribution network within the supply areas jurisdiction is a combination of different network topologies.

Supply authorities do not necessarily keep a record of the reliability indices of the different network topologies. For these parameters, an insightful requirement and preference of the different network topologies shall be selected by the user. The degree of importance of the respective required level of reliability of each respective network shall be compared.

4.2.2.3 Social and Environmental

Some of the social and environmental factors are built into the national standard ADMD calculation as different LSM levels have their respective design ADMD's. Case in point, the items covered by the national standard include the consumer classification level, average household monthly income and seasonal climatic conditions. The calculation of the ADMD thus takes into cognisance the envisioned level of service to be provided within the development. The main social and environmental issue to be addressed by the model is primarily the aesthetic perspective. In the model the user shall be able to perform the selection of the level of importance of the aesthetic appeal of the different network design topologies.

4.3 AHP MODELLING

The modelling of the evaluation model shall be carried out with the implementation of the AHP, which will result in the design network topology being ranked based on the pair-wise comparison of the criteria provided above. The comparison of the criteria essentially results in the determination of the weight of each criterion relative to each other. In the application of AHP, consistency in the comparison matrix is essential and has to be fulfilled.

Therefore, the check for consistency is implemented through the consistency ratio (CR) which is a ratio of the comparison matrix consistency index and the consistency index of a random sample. In the model, the criteria are defined as follows:

- Financial.
- Reliability.
- Social and Environmental.

Once the weights of the criteria have been calculated, the criteria shall then have a ranking which indicates which criteria takes preference over the other. A pair-wise comparison shall be performed on the available alternatives on each individual criterion. The check for consistency shall be carried on the resultant priorities of the alternatives on each criterion to ensure consistency. In the model the alternatives are defined as follows:

- Underground.
- Overhead.
- Hybrid.

The results shall be the priorities of the alternatives (underground, overhead and hybrid) in relation to each of the respective criterion (financial, reliability, social and environmental). At this stage, we shall be in a position of knowing exactly how the three available network design topologies compare in relation to the evaluation criteria.

The penultimate stage in the evaluation model is the ranking of the network design topologies using the criteria weights and the priorities of the network design topologies in relation with each criterion. This is provided by the sum product of the weight of each criterion and the priorities of the network design topologies with respect to each of the criterion. The final stage of the ranking process shall include sensitivity analysis in which different scenarios are evaluated. The pair-wise comparison shall be performed using the scale developed by Thomas Saaty.

Level of Importance	Definition
1	Equal importance
2	Weak or Slight
3	Moderate Importance
4	Moderate Plus
5	Strong Importance
6	Strong Plus
7	Very Strong / Demonstrated Importance
8	Very, Very Strong
9	Extreme Importance

Table 4-1: Fundamental Scale for Pair-Wise Comparisons Using Absolute Numbers

The process flow of the entire model from the load requirement determination to the ranking of the network design topology is detailed schematically. The illustration covers the entire process from the pair-wise comparison to achieving the final ranking of the different network design topologies inclusive of performing the sensitivity analysis. The summary of the AHP modelling process is presented in the figure below:

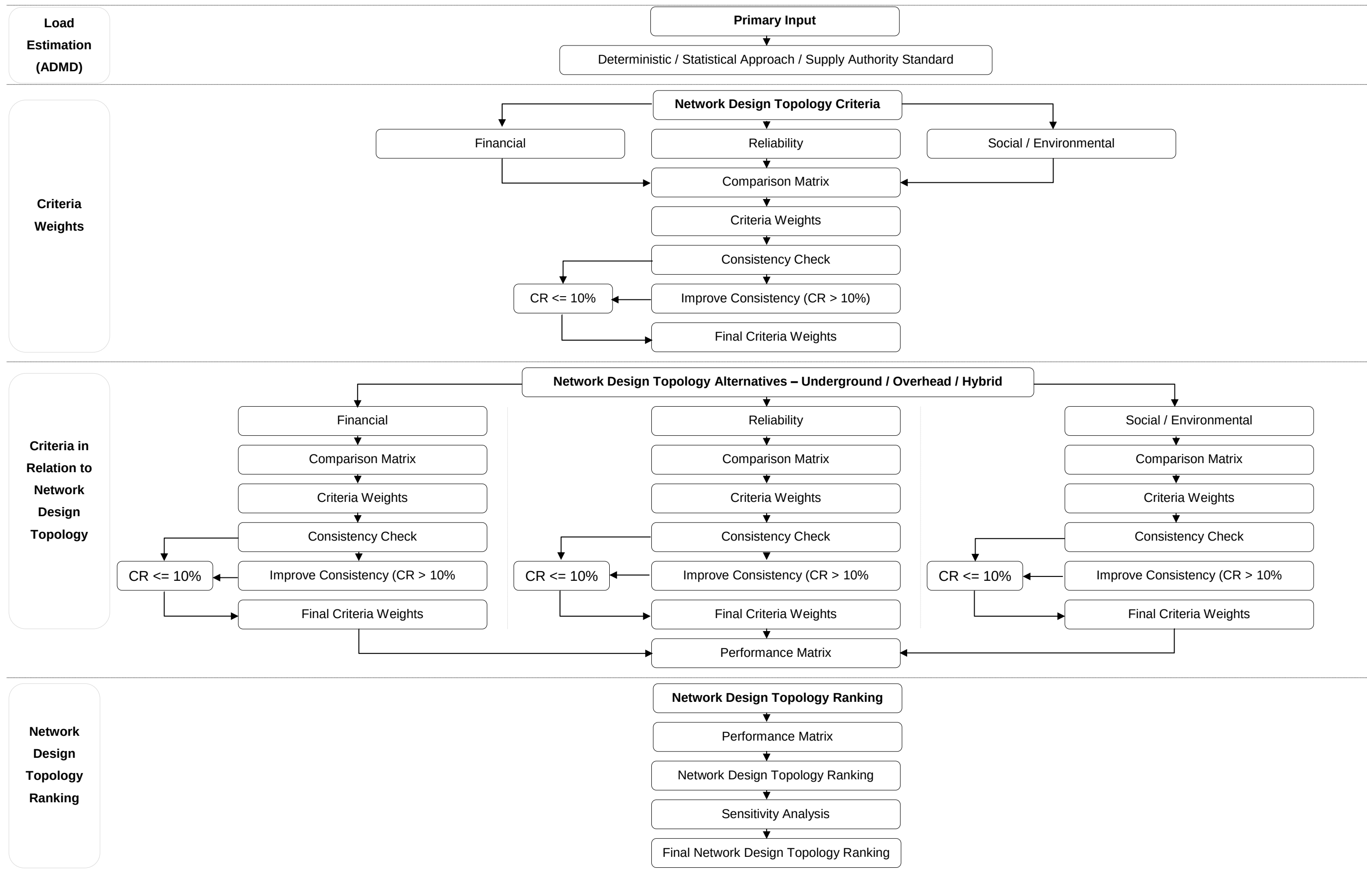


Figure 4-2: AHP Modelling Electrification Network Design Topology Process Flow

4.3.1 Comparison Matrix

A comparison matrix is defined as a matrix which consists of pair-wise comparison elements. Opposite matrix elements shall have reciprocal values. The model shall consist of four (4) comparison matrices which shall be derived. The first comparison matrix shall be on the criteria while the remaining three (3) shall be for each criterion in relation to the different network design topologies. The pair-wise scale comparison shall be used to determine the entries of the comparison matrix.

$$X_{comparison} = \begin{pmatrix} x_{11} & x_{12} & x_{13} \\ x_{21} & x_{22} & x_{23} \\ x_{31} & x_{32} & x_{33} \end{pmatrix} \quad \dots (1) \text{ (Saaty, 1987)}$$

4.3.2 Calculation of the Geometric Mean & Weights (Eigen Vectors)

The evaluation model uses the comparison matrix to calculate the respective weights of either the criteria or of each criterion in relation to the different network topologies. The calculation of the weights shall then follow, which is essentially an Eigen vector in linear algebra terms. An Eigen vector is defined as a column matrix which only results in a scale factor of a matrix. In the evaluation model, a simple approximation method shall be used and not the complex linear algebraic matrix methods.

The geometric mean approximation method is implemented to determine the Eigen vector. The geometric mean is simply defined as the n^{th} root of a product of n numbers. In the model, this is achieved by calculating the n^{th} root of the product of the entries of each row. The resultant geometric mean of each row is summed and the entries of the Eigen vector are provided by the quotient of each row geometric mean and the sum of all the rows geometric means. This results in a normalised Eigen vector. The calculation of the Eigen vector is represented by the formulae below, geometric mean (2) and Eigen vector (3):

$$\text{Geometric Mean} = \left[\prod_{i=1}^3 x_{ij} \right]^{\frac{1}{3}} = \sqrt[3]{x_{i1} x_{i2} x_{i3}} \quad \dots (2) \text{ (Coyle, 2004)}$$

Where i – row and j is the column of the 3×3 comparison matrix

$$W = Weight$$

$$= \frac{1}{\left(\sum_{j=1}^3 \left(\left[\prod_{i=1}^3 x_{ij} \right]^{\frac{1}{3}} \right) \right)} \begin{pmatrix} \left[\prod_{i=1}^3 x_{i1} \right]^{\frac{1}{3}} \\ \left[\prod_{i=1}^3 x_{i2} \right]^{\frac{1}{3}} \\ \left[\prod_{i=1}^3 x_{i3} \right]^{\frac{1}{3}} \end{pmatrix} \quad \dots (3) (Coyle, 2004)$$

$$= \begin{pmatrix} w_{11} \\ w_{21} \\ w_{31} \end{pmatrix} \quad \dots (4)$$

The weights of the respective criteria and that of each criterion in relation to the alternatives shall be calculated using the formulae above.

4.3.3 Consistency Index and Consistency Ratio

The evaluation model also implements the consistency checking mechanism of the AHP to ensure that the comparison matrices are consistent. The comparison matrix is multiplied with the calculated Eigen vector which results in an Eigen column matrix. The resultant Eigen column matrix is then divided with the Eigen vector to provide the approximation of the $Lambda_{max}$ column matrix. The geometric mean of the $Lambda_{max}$ column matrix is calculated, this is used as the $Lambda_{max}$ value in the evaluation model. This resultant value is a checking mechanism which provides the order of the matrix and is used for checking purposes.

$$EigenColumn = EC$$

$$= X_{comparison} * Weight$$

$$= \begin{pmatrix} x_{11} & x_{12} & x_{13} \\ x_{21} & x_{22} & x_{23} \\ x_{31} & x_{32} & x_{33} \end{pmatrix} \left[\frac{1}{\left(\sum_{j=1}^3 \left(\left[\prod_{i=1}^3 x_{ij} \right]^{\frac{1}{3}} \right) \right)} \begin{pmatrix} \left[\prod_{i=1}^3 x_{i1} \right]^{\frac{1}{3}} \\ \left[\prod_{i=1}^3 x_{i2} \right]^{\frac{1}{3}} \\ \left[\prod_{i=1}^3 x_{i3} \right]^{\frac{1}{3}} \end{pmatrix} \right] \quad \dots (5) (Coyle, 2004)$$

$$= \begin{pmatrix} ec_{11} \\ ec_{21} \\ ec_{31} \end{pmatrix} \quad \dots (6)$$

$$\begin{aligned}
Lamda_{max} &= \frac{W}{EC} \\
&= \left(\begin{matrix} Lamda_{max_{11}} \\ Lamda_{max_{21}} \\ Lamda_{max_{31}} \end{matrix} \right) \quad \dots (7)(Coyle, 2004)
\end{aligned}$$

$$\begin{aligned}
Lamda_{max} \text{ Value} &= \text{Geometric Mean of } Lamda_{max} \\
&= \left[\prod_{i=1}^3 Lamda_{max_{i1}} \right]^{\frac{1}{3}} \\
&= \sqrt[3]{Lamda_{max_{11}} Lamda_{max_{21}} Lamda_{max_{31}}} \quad \dots (8)(Coyle, 2004)
\end{aligned}$$

The critical checking mechanism is the one which resolves the consistency of the comparison matrix. This is calculated using the $Lamda_{max}$ value and the order of the matrix. In the model, the order of the matrix (n) shall always be 3, thus the consistency index shall be calculated using the following formula:

$$\text{Consistency Index} = \frac{(Lamda_{max} - n)}{n - 1} \quad \dots (9) (Coyle, 2004)$$

$$\text{Consistency Ratio} = \frac{CI}{CI_{random \text{ sample}}} \quad \dots (10) (Coyle, 2004)$$

The resultant consistency index is then divided with the consistency index of a random sample derived by Saaty and in the model this shall always correspond to a matrix of an order of 3 – the corresponding consistency index is 0.58. The quotient resulting from the division of the consistency index and the random consistency index is defined as the consistency ratio. Literature dictates that, this needs to be always to a maximum of 0.1 (Franek & Kresta, 2014:168; Ishizaka & Labib, 2011:14340). This translates to the pair-wise comparison being compared having an “error” of consistency limited to 10%. A truly consistent comparison matrix results in the consistency ratio of 0, as the $Lamda_{max}$ value is equal to the order of the matrix. This is evidently easy to demonstrate on a matrix with an order of 2. In the case that the ratio is above 10%, the user shall be prompted to review and improve the ratio.

4.3.3.1 Improving Consistency Ratio

There are several methods in improving the consistency ratio. These are well documented in literature, the model uses the least complicated procedure (Saaty, 2003:88; Xu & Xiong, 2017). This involves the review of the calculated weights and the comparison matrix. This shall be achieved by having a check matrix which shall be the product of the comparison matrix elements and the corresponding weight ratio related to the element. This is provided by the formulae below:

$$C_{comparison} = x_{ij} * \frac{w_j}{w_i} = \begin{pmatrix} x_{11} & x_{12} & x_{13} \\ x_{21} & x_{22} & x_{23} \\ x_{31} & x_{32} & x_{33} \end{pmatrix} * \frac{w_j}{w_i} = \begin{pmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{pmatrix} \quad \dots (11) \text{ (Coyle, 2004)}$$

Where the ratio w_j / w_i corresponds with the respective entries of the calculated weights of the column matrix.

The resultant entries of the check comparison matrix shall be analysed. The largest check matrix entry shall be the most inconsistent. In order to improve the consistency of the comparison matrix, the equivalent element of the comparison matrix with its reciprocal element shall be replaced with the ratio w_i / w_j . These respective elements of the comparison matrix shall be updated and the process for checking consistency shall be calculated in order to satisfy the condition of having the error in consistency being less than 10%.

4.3.4 Network Design Topology Ranking

This step in the evaluation model consists of forming a matrix composed of the weight of each criterion in relation to the different network design topologies. This matrix shall be referred to as the network design topology performance matrix. This is essentially a summary of each defined criterion with respect to the different network design topology alternatives. In order to determine the ranking of the different network design topologies, the product of the performance matrix with the weight of the different network topologies is calculated.

The resultant sum product of the weights of the criteria and that of each criterion in relation to the alternatives shall provide the ranking of the network topologies. This shall then be the ranking of the different network design topologies based on the fulfilment of the primary input (the load requirement), financial costing of actual completed similar electrification projects and sustainably consistent subjective judgements of the defined criteria.

$$P_{Performance} = W_{Financial} \quad W_{Reliability} \quad W_{Social \& Environmental}$$

$$= \begin{pmatrix} W_{Financial_{11}} & W_{Reliability_{11}} & W_{Social \& Environmental_{11}} \\ W_{Financial_{21}} & W_{Reliability_{21}} & W_{Social \& Environmental_{21}} \\ W_{Financial_{31}} & W_{Reliability_{31}} & W_{Social \& Environmental_{31}} \end{pmatrix} \dots (12) \text{ (Coyle, 2004)}$$

$$= \begin{pmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & p_{33} \end{pmatrix} \dots (13)$$

$$R_{Network \ Topology \ Ranking} = P_{Performance} \quad W_{Comparison}$$

$$= \begin{pmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & p_{33} \end{pmatrix} * \begin{pmatrix} w_{11} \\ w_{21} \\ w_{31} \end{pmatrix} \dots (14) \text{ (Coyle, 2004)}$$

$$= \begin{pmatrix} r_{11} \\ r_{21} \\ r_{31} \end{pmatrix} \dots (15)$$

4.3.5 Sensitivity Analysis

The overall network topology ranking in the evaluation model is largely influenced by the resultant weights of the comparison matrix of the criteria. Sensitivity analysis in the model is essentially the “what-if” analysis to see how different the results would be in the event that the weights of the criteria were to change. The primary objective of the analysis is to determine which factors drive our ranking and how firm is our ranking system. This will determine if preferences change what will be the effect on the ranking. In the model, the user will have the option of changing the calculated weights to determine the effect of the changes on the network design topology rankings. The default scenarios shall be as follows:

- i) equal weights of the comparison matrix.
- ii) highest ranking criteria leading and remaining two alternatives equal in weight.

$$R(SA)_{Network \ Topology \ Ranking \ Sensitivity \ Analysis} = P_{Performance} \quad W_{SA \ Equal \ Weights} \dots (16)$$

$$R(SA)_{Network \ Topology \ Ranking \ Sensitivity \ Analysis} = P_{Performance} \quad W_{SA \ Different \ Weights} \dots (17)$$

4.4 CHAPTER SUMMARY

The details of the evaluation model were presented in this chapter. This commenced with the framework of the model, a detailed process flow and with the conclusion of the detailed different aspects of the evaluation model. From this chapter, we are now in a position to rank the different network design topologies. In the next chapter, the results of the evaluation model shall be presented with an application of a case study with the evaluation model validation carried out by the comparison of the developed evaluation model results with those of an educational / commercial multi-criteria decision-making software package – Super Decisions.

CHAPTER 5

5. RESULTS AND CASE STUDY OF EVALUATION MODEL

5.1 INTRODUCTION

The design of the evaluation model from fundamental elements with the application of the AHP as a mean to achieve a ranking of the different network design topology options was presented in the previous chapter. In this chapter of the dissertation, the results of the evaluation model are presented, together with the shortcomings and advantages. The verification of the model input shall be carried out with the validation of the model results carried through the comparison of the results with those of the internationally used educational / commercial package used for multi-criteria decision-making, Super Decisions.

The entire evaluation model is based on the widely available and accessible Microsoft Excel package. The primary motivation to develop the model through Microsoft Excel was to ensure that it keeps to the theme of keeping the work simple and user friendly for the end user. The idea is to achieve the required functionality of deciding which network design topology option to implement based on the technically sound and rational means. The rationality of the model is coupled with the fulfilment of the load requirement first and then the utilisation of readily available previous project information in order to attain the desired sustainable network design topology option.

The evaluation model is cost effective and a sustainable network topology decision is achieved with the use of information readily available. The evaluation model is purposely built as a working tool from a consulting perspective particularly specific to the residential electrification design environment to aid supply authorities and developers in achieving a sustainable network design topology.

5.2 EVALUATION MODEL GRAPHICAL USER INTERFACE

The evaluation model user interface is kept simple, easy to read with the interpretation of the summary of results. The entire evaluation model results summary from the load estimation, criteria weights, design topology ranking with the sensitivity analysis are presented in a printable A3 sized page. Each of these components of the evaluation model shall then be detailed individually in the subsequent sub-sections.

The snap shots from the overview together with the actual component detail shall be bundled together in order to follow the component detail with the entire model overview. The overview of the user interface of the model is indicated in the figure below:

RESIDENTIAL ELECTRIFICATION DESIGN TOPOLOGY EVALUATION MODEL

LOAD ESTIMATION									
LOAD ESTIMATION RESULT SUMMARY									
APPROACH									
DESIGN ADMD					kVA				

NETWORK DESIGN TOPOLOGY COMPARISON MATRIX & CRITERIA WEIGHTS

COMPARISON MATRIX RESULT SUMMARY

	FINANCIAL	RELIABILITY	SOCIAL/ENVIRONMENTAL	CRITERIA WEIGHTS
FINANCIAL				
RELIABILITY				
SOCIAL/ENVIRONMENTAL				
CONSISTENCY RATIO (IN %)				

FINANCIAL COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY

FINANCIAL COMPARISON MATRIX RESULT SUMMARY

FINANCIAL	UNDERGROUND	OVERHEAD	HYBRID	FINANCIAL WEIGHTS	NORMALISED COST PER STAND VECTOR	CAPITAL COST PER STAND	LIFE CYCLE COST PER STAND OVER 20 YEARS
UNDERGROUND							
OVERHEAD							
HYBRID							
CONSISTENCY RATIO (IN %)							

RELIABILITY COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY

RELIABILITY COMPARISON MATRIX RESULT SUMMARY

RELIABILITY	UNDERGROUND	OVERHEAD	HYBRID	RELIABILITY WEIGHTS
UNDERGROUND				
OVERHEAD				
HYBRID				
CONSISTENCY RATIO (IN %)				

SOCIAL / ENVIRONMENTAL COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY

SOCIAL / ENVIRONMENTAL COMPARISON MATRIX RESULT SUMMARY

SOCIAL/ENVIRONMENTAL	UNDERGROUND	OVERHEAD	HYBRID	SOCIAL/ENVIRONMENTAL WEIGHTS
UNDERGROUND				
OVERHEAD				
HYBRID				
CONSISTENCY RATIO (IN %)				

NETWORK DESIGN TOPOLOGY PERFORMANCE MATRIX

PERFORMANCE MATRIX RESULT SUMMARY

	FINANCIAL	RELIABILITY	SOCIAL / ENVIRONMENTAL	CRITERIA WEIGHTS
UNDERGROUND				
OVERHEAD				
HYBRID				
OVERALL CONSISTENCY RATIO (IN %)				

NETWORK DESIGN TOPOLOGY RANKING

NETWORK TOPOLOGY RANKING RESULT SUMMARY

RANKING		
RANKING 1		
RANKING 2		
RANKING 3		

NETWORK DESIGN TOPOLOGY SENSITIVITY ANALYSIS

SENSITIVITY ANALYSIS

	ALL EQUAL WEIGHTS	RANKING	TWO EQUAL WEIGHTS	RANKING
RANKING 1				
RANKING 2				
RANKING 3				

FINAL NETWORK DESIGN TOPOLOGY RANKING

FINAL TOPOLOGY RANKING SUMMARY

RANKING	
RANKING 1	
RANKING 2	
RANKING 3	

RESET SHEET ALL DATA

Figure 5-1: Electrification Network Design Topology Evaluation Model User Interface

5.2.1 Load Estimation

The load estimation is the primary input in the evaluation model. Within this option the following three options (Statistical / Probabilistic, Deterministic or Supply Authority Standard) are available to determine the design ADMD of the specific development:

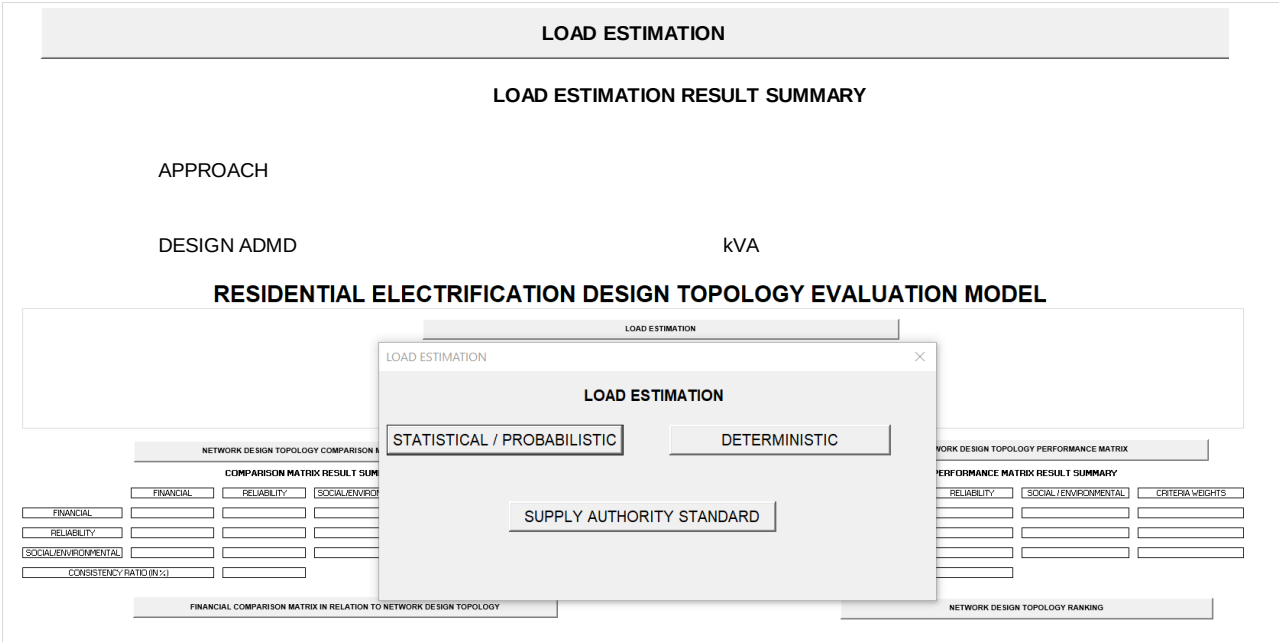


Figure 5-2: Load Estimation Options

5.2.1.1 Statistical / Probabilistic Approach

The statistical / probabilistic approach requires statistical load data as per SANS 507 in order to determine the design ADMD. Supply authorities (predominately Eskom) normally provide the α and β parameters for the particular LSM in order to determine the design ADMD.

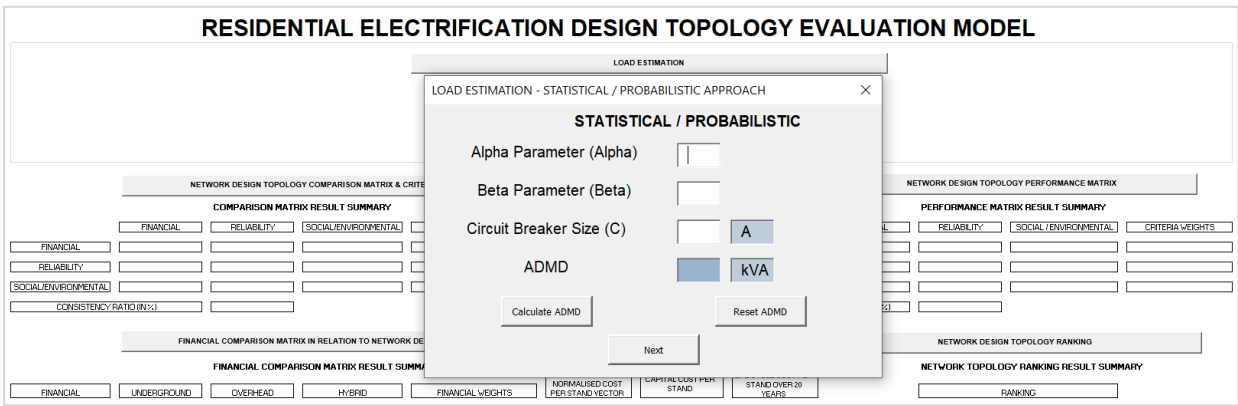


Figure 5-3: Statistical / Probabilistic Approach

5.2.1.2 Deterministic Approach

More often than not, supply authorities utilise the deterministic approach in the computation of the design ADMD. This is also utilised in most private residential development to determine the required design ADMD.

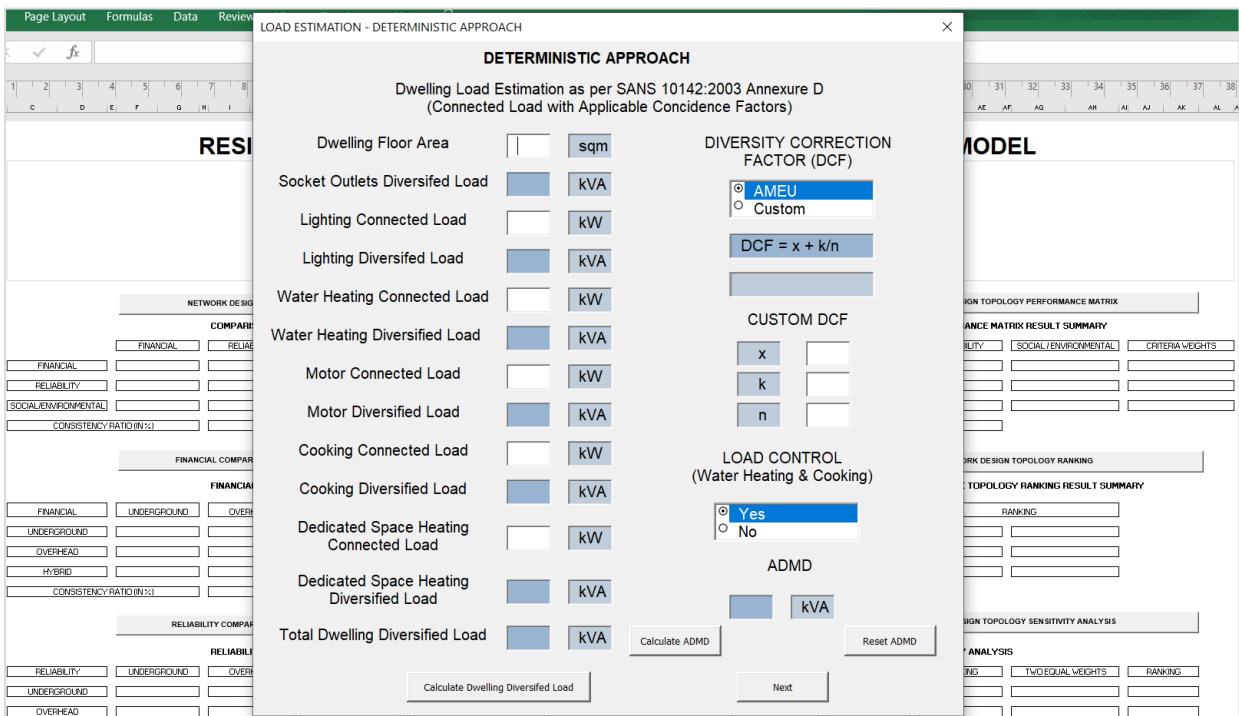


Figure 5-4: Deterministic Approach

5.2.1.3 Supply Authority Standard Approach

In most cases, supply authorities tend to standardise their design ADMD requirement so as to have uniformity within their supply area. It is not the purpose of the evaluation model to determine whether the selected ADMD is correctly calculated or not. The importance of the correct calculation of the design ADMD was highlighted as part of the literature survey in Chapter 2 and the network design topology investigation in Chapter 3 of this dissertation.

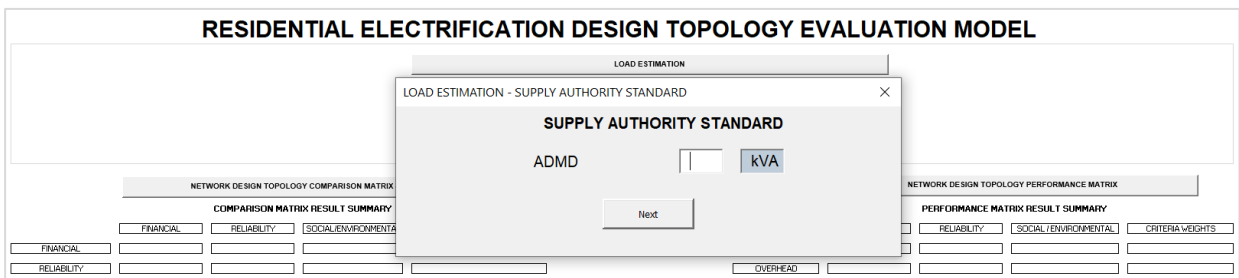


Figure 5-5: Supply Authority Standard

5.2.2 Network Design Topology Criteria Comparison Matrix

The next phase in the evaluation model consists of performing pair-wise comparison on the desired network design topology criteria. This comparison is not specific to any design topology but strictly on what is required of the desired network topology. The pair-wise comparison is applicable on all the criteria and for each criterion in relation to the network design topology. This pair-wise comparison is carried out on all comparison matrices using the absolute scale from 1 to 9 and its applicable inverse.

NETWORK DESIGN TOPOLOGY COMPARISON MATRIX & CRITERIA WEIGHTS

COMPARISON MATRIX RESULT SUMMARY

	FINANCIAL	RELIABILITY	SOCIAL/ENVIRONMENTAL	CRITERIA WEIGHTS
FINANCIAL				
RELIABILITY				
SOCIAL/ENVIRONMENTAL				

PAIRWISE COMPARISON SCALE
×

LEVEL OF IMPORTANCE	DEFINITION
1	Equal Importance
2	Weak or Slight
3	Moderate Importance
4	Moderate Plus
5	Strong Importance
6	Strong Plus
7	Very Strong / Demonstrated Importance
8	Very, Very Strong
9	Extreme Importance

Figure 5-6: Pairwise Comparison Scale

From the pair-wise comparison of the criteria, the weights of the criteria shall be known. In the model three pair-wise comparisons are performed and the model then calculates the applicable inverse of the remaining three pair-wise comparisons. The three pair-wise comparisons are namely:

- Financial-Reliability.
- Financial-Social/Environmental.
- Reliability-Social/Environmental.

These are generally comparison matrix entries (1, 2), (1, 3) and (2, 3). The three criteria defined are as follows:

- Financial.
- Reliability.
- Social / Environmental.

NETWORK DESIGN TOPOLOGY COMPARISON MATRIX

Enter Comparison Matrix Entries (White Cells)

	Financial	Reliability	Social / Environmental
Financial	1		
Reliability		1	
Social / Environmental			1

Calculate Criteria Weights

Financial	
Reliability	
Aesthetics / Social	

Calculate Inverse Matrix Entries

Reset Matrix Entries

Check Consistency

Consistency Ratio:

Improve Consistency - Calculate Check Matrix

	Financial	Reliability	Social / Environmental
Financial			
Reliability			
Social / Environmental			

Improved Comparison Matrix

	Financial	Reliability	Social / Environmental	Improved Matrix Criteria Weights
Financial				
Reliability				
Social / Environmental				

Largest Check Matrix Entry

Improved Consistency Ratio (Largest Entry Method)

Next

Figure 5-7: Network Design Topology Criteria

5.2.3 Criteria In Relation To Network Design Topology

Each of the three criterion defined above shall then undergo a process in which pair-wise comparison against the three design topology alternatives available is undertaken. In the financial criteria, the actual cost per stand for previous projects at the same design ADMD are required as an input.

The resultant cost column vector is then normalised in order to include the actual cost per stand of the previous projects at the same design ADMD. The respective cost per stand is also able to incorporate the life cycle cost element for the different design topology alternatives.

NETWORK DESIGN TOPOLOGY COMPARISON MATRIX & CRITERIA WEIGHTS							
COMPARISON MATRIX RESULT SUMMARY							
	FINANCIAL	RELIABILITY	SOCIAL/ENVIRONMENTAL	CRITERIA WEIGHTS			
FINANCIAL							
RELIABILITY							
SOCIAL/ENVIRONMENTAL							
CONSISTENCY RATIO (IN %)							
FINANCIAL COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY							
FINANCIAL COMPARISON MATRIX RESULT SUMMARY							
FINANCIAL	UNDERGROUND	OVERHEAD	HYBRID	FINANCIAL WEIGHTS	NORMALISED COST PER STAND VECTOR	CAPITAL COST PER STAND	LIFE CYCLE COST PER STAND OVER 20 YEARS
UNDERGROUND							
OVERHEAD							
HYBRID							
CONSISTENCY RATIO (IN %)							
RELIABILITY COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY							
RELIABILITY COMPARISON MATRIX RESULT SUMMARY							
RELIABILITY	UNDERGROUND	OVERHEAD	HYBRID	RELIABILITY WEIGHTS			
UNDERGROUND							
OVERHEAD							
HYBRID							
CONSISTENCY RATIO (IN %)							
SOCIAL / ENVIRONMENTAL COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY							
SOCIAL / ENVIRONMENTAL COMPARISON MATRIX RESULT SUMMARY							
SOCIAL/ENVIRONMENTAL	UNDERGROUND	OVERHEAD	HYBRID	SOCIAL/ENVIRONMENTAL WEIGHTS			
UNDERGROUND							
OVERHEAD							
HYBRID							
CONSISTENCY RATIO (IN %)							

Figure 5-8: Criteria in Relation to Network Design Topology

FINANCIAL COMPARISON MATRIX

FINANCIAL COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY

Enter Comparison Matrix Entries (White Cells)

Financial	Underground	Overhead	Hybrid	Normalised Cost per Stand Vector	Capital Cost per Stand	LCC per Stand Over 20 Years
Underground	1					
Overhead		1				
Hybrid			1			

Specified ADMD: kVA

Calculate Criteria Weights

Insert Cost per Stand @ Design ADMD

Calculate Inverse Matrix Entries

Reset Matrix Entries

Underground

Overhead

Hybrid

Check Consistency

Consistency Ratio:

Improve Consistency - Calculate Check Matrix

	Underground	Overhead	Hybrid
Underground			
Overhead			
Hybrid			

Largest Check Matrix Entry:

Improved Comparison Matrix

	Underground	Overhead	Hybrid	Improved Matrix Criteria Weights
Underground				
Overhead				
Hybrid				

Improved Consistency Ratio (Largest Entry Method):

Next

Figure 5-9: Financial Comparison Matrix in Relation to Network Design Topology

FINANCIAL COMPARISON MATRIX

FINANCIAL COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY

Enter Comparison Matrix Entries (White Cells)

Financial	Underground	Overhead	Hybrid	Normalised Cost per Stand Vector	Capital Cost per Stand	LCC per Stand Over 20 Years
Underground	1					
Overhead		1				
Hybrid			1			

Specified ADMD: kVA

Calculate Criteria Weights

Insert Cost per Stand @ Design ADMD

Calculate Inverse Matrix Entries

Reset Matrix Entries

Underground

Overhead

Hybrid

Annual Operational Costs - Underground Cost per Stand ?

Enter Annual Operational Costs as Percentage of Initial Capital Costs - Annual Underground Network Operational Costs Ranges Between 3.33% to 6.25% with Average of 4.79%

Enter Annual Operational Costs for Underground Cost Per Stand Here:

OK **Cancel**

Improve Consistency - C

	Underground	Overhead	Hybrid
Underground			
Overhead			
Hybrid			

Largest Check Matrix Entry:

Improved Comparison Matrix

	Underground	Overhead	Hybrid	Improved Matrix Criteria Weights
Underground				
Overhead				
Hybrid				

Improved Consistency Ratio (Largest Entry Method):

Next

Figure 5-10: Financial Comparison Matrix in Relation to Network Design Topology – Life Cycle Cost Functionality

RELIABILITY COMPARISON MATRIX

RELIABILITY COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY

Enter Comparison Matrix Entries (White Cells)

	Underground	Overhead	Hybrid
Underground	1		
Overhead		1	
Hybrid			1

Consistency Ratio

Calculate Criteria Weights

Underground	
Overhead	
Hybrid	

Improve Consistency - Calculate Check Matrix

	Underground	Overhead	Hybrid
Underground			
Overhead			
Hybrid			

Largest Check Matrix Entry

Improved Comparison Matrix

	Underground	Reliability	Aesthetics / Social	Improved Matrix Criteria Weights
Underground				
Overhead				
Hybrid				

Improved Consistency Ratio (Largest Entry Method)

Figure 5-11: Reliability Comparison Matrix in Relation to Network Design Topology

SOCIAL / ENVIRONMENTAL COMPARISON MATRIX

SOCIAL / ENVIRONMENTAL COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY

Enter Comparison Matrix Entries (White Cells)

	Underground	Overhead	Hybrid
Underground	1		
Overhead		1	
Hybrid			1

Consistency Ratio

Calculate Criteria Weights

Underground	
Overhead	
Hybrid	

Improve Consistency - Calculate Check Matrix

	Underground	Overhead	Hybrid
Underground			
Overhead			
Hybrid			

Largest Check Matrix Entry

Improved Comparison Matrix

	Underground	Overhead	Hybrid	Improved Matrix Criteria Weights
Underground				
Overhead				
Hybrid				

Improved Consistency Ratio (Largest Entry Method)

Figure 5-12: Social / Environmental Comparison Matrix in Relation to Network Design Topology

5.2.4 Network Design Topology Performance Matrix

The performance matrix provides a summary of the weights of each criterion in relation to the network design topology alternatives available. This summary is represented in matrix form.

NETWORK DESIGN TOPOLOGY PERFORMANCE MATRIX

PERFORMANCE MATRIX RESULT SUMMARY

	FINANCIAL	RELIABILITY	SOCIAL / ENVIRONMENTAL	CRITERIA WEIGHTS
UNDERGROUND				
OVERHEAD				
HYBRID				
OVERALL CONSISTENCY RATIO (IN %)				

NETWORK DESIGN TOPOLOGY PERFORMANCE MATRIX
×

NETWORK DESIGN TOPOLOGY PERFORMANCE MATRIX

	Financial	Reliability	Social / Environmental		Criteria Weights
Underground				Financial	
Overhead				Reliability	
Hybrid				Social / Environmental	
Overall Consistency Ratio					

Calculate Performance Matrix Entries

Next

Figure 5-13: Network Design Topology Performance Matrix

5.2.5 Network Design Topology Ranking

The ranking of the network design topology is computed using the matrix product of the performance matrix and the criteria weights. The network design topology options are ranked accordingly with the normalised ranking indicated in the evaluation model.

NETWORK DESIGN TOPOLOGY RANKING

NETWORK TOPOLOGY RANKING RESULT SUMMARY

RANKING

RANKING 1

RANKING 2

RANKING 3

NETWORK DESIGN TOPOLOGY RANKING

Ranking

Ranking 1

Ranking 2

Ranking 3

Calculate Topology Ranking

Next

Figure 5-14: Network Design Topology Ranking

5.2.6 Network Design Topology Sensitivity Analysis

A network design topology sensitivity analysis exercises is then performed to the ranking calculated in above. Two scenarios analysed as follows:

- All Criteria Weights Equal.

119

- The Highest-Ranking Criterion Weight Retained and Remaining Two Weights Equally Balanced.

NETWORK DESIGN TOPOLOGY SENSITIVITY ANALYSIS

SENSITIVITY ANALYSIS

	ALL EQUAL WEIGHTS	RANKING	TWO EQUAL WEIGHTS	RANKING
RANKING 1				
RANKING 2				
RANKING 3				

NETWORK DESIGN TOPOLOGY SENSITIVITY ANALYSIS
×

NETWORK DESIGN TOPOLOGY SENSITIVITY ANALYSIS

ALL EQUAL WEIGHTS

TWO EQUAL WEIGHTS

Ranking 1				Ranking 1			
Ranking 2				Ranking 2			
Ranking 3				Ranking 3			

Calculate Topology Sensitivity Analysis - All Equal Weights

Calculate Topology Sensitivity Analysis - Two Equal Weights

Next

Figure 5-15: Network Design Topology Ranking

5.2.7 Network Design Topology Final Ranking

The final ranking of the network design topology compares the result obtained with the results of the sensitivity analysis exercise performed. The final ranking is then provided.

FINAL NETWORK DESIGN TOPOLOGY RANKING

FINAL TOPOLOGY RANKING SUMMARY

		RANKING
RANKING 1		
RANKING 2		
RANKING 3		

FINAL NETWORK DESIGN TOPOLOGY RANKING

FINAL NETWORK DESIGN TOPOLOGY RANKING

Ranking

Ranking 1		
Ranking 2		
Ranking 3		

Calculate Final Topology Ranking

Next

Figure 5-16: Final Network Design Topology Ranking

5.2.8 Reset All Sheet Entries

This is used to clear all the data entries in the sheet.

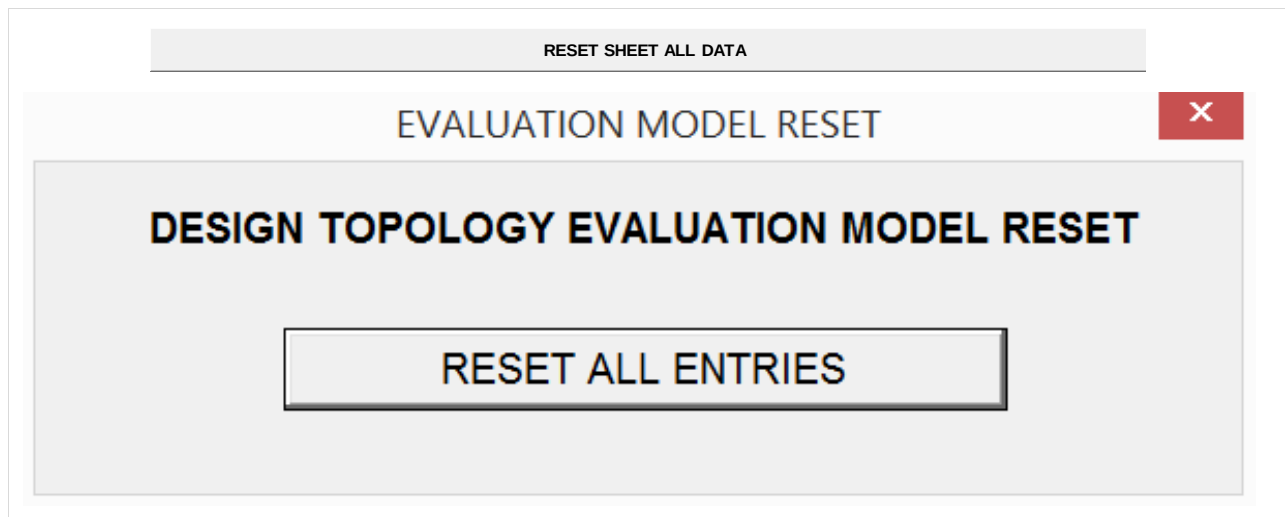


Figure 5-17: Reset Evaluation Model Data Entries

5.3 EVALUATION MODEL CASE STUDY

5.3.1 Background

In testing the newly developed evaluation model, a new development in the West of Johannesburg was used. The development which is in the concept and feasibility stage consists of approximately 11 000 residential housing units. The split in terms of residential housing units is 8 000 high density Reconstruction and Development Programme (RDP) units (walk-up units) and 3 000 single residential stands which are Finance Linked Individual Subsidy Programme (FLISP) units. The supply authority in the development is the City Power Johannesburg.

Our Client appointed us as the consulting electrical engineers for the development responsible for all the six Engineering Council of South Africa (ECSA) stages of the project from Inception to Close-Out. Due to the size of the development and cash flow restrictions, the entire development is scheduled to be rolled over a period of 5 calendar years and stretching over 6 municipal financial years.

Part of the Inception, Concept and Viability ECSA stages, the scope of works was to present the project costing to the Client. In order to be able to present the development costing, one of the requirements involves the taking the decision which network design topology is to be implemented.

The different available network topologies do have different cost implications which can ultimately render the development feasible or not to our Client. Simultaneously, the design topology has to comply with the requirements of the supply authority within the development. For the development, no bulk supply electrical infrastructure is available.

Thus, based on the development load requirements, in-line with the supply authorities master planning in and around the area, a new bulk in-take substation was proposed to supply the development. Our Client's requirements were to provide a cost-effective solution to service the development.

5.3.2 Results Summary

RESIDENTIAL ELECTRIFICATION DESIGN TOPOLOGY EVALUATION MODEL											
LOAD ESTIMATION											
LOAD ESTIMATION RESULT SUMMARY											
APPROACH				Supply Authority Standard							
DESIGN ADMD				5.00		kVA					
NETWORK DESIGN TOPOLOGY COMPARISON MATRIX & CRITERIA WEIGHTS					NETWORK DESIGN TOPOLOGY PERFORMANCE MATRIX						
COMPARISON MATRIX RESULT SUMMARY					PERFORMANCE MATRIX RESULT SUMMARY						
	FINANCIAL	RELIABILITY	SOCIAL/ENVIRONMENTAL	CRITERIA WEIGHTS		FINANCIAL	RELIABILITY	SOCIAL / ENVIRONMENTAL	CRITERIA WEIGHTS		
FINANCIAL	1	3.5568	9.0000	0.6938	UNDERGROUND	0.5310	0.7770	0.6370	0.6938		
RELIABILITY	0.2811	1	5.0000	0.2448	OVERHEAD	0.0940	0.0700	0.1050	0.2448		
SOCIAL/ENVIRONMENTAL	0.1110	0.2000	1	0.0614	HYBRID	0.3760	0.1530	0.2580	0.0614		
CONSISTENCY RATIO (IN %)		4.42%			OVERALL CONSISTENCY RATIO (IN %)		0.001%				
FINANCIAL COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY					NETWORK DESIGN TOPOLOGY RANKING						
FINANCIAL COMPARISON MATRIX RESULT SUMMARY					NETWORK TOPOLOGY RANKING RESULT SUMMARY						
FINANCIAL	UNDERGROUND	OVERHEAD	HYBRID	FINANCIAL WEIGHTS	NORMALISED COST PER STAND VECTOR	CAPITAL COST PER STAND	LIFE CYCLE COST PER STAND OVER 20 YEARS	RANKING			
UNDERGROUND	1	4.4380	1.8023	0.5306	0.5270	R 31 000.00	R 57 728.20	RANKING 1	Underground	0.5975	
OVERHEAD	0.2250	1	0.1950	0.0936	0.5940	R 23 500.00	R 65 038.60	RANKING 2	Hybrid	0.3140	
HYBRID	0.5548	5.1210	1	0.3758	0.6080	R 27 750.00	R 66 611.10	RANKING 3	Overhead	0.0885	
CONSISTENCY RATIO (IN %)		5.07%									
RELIABILITY COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY					NETWORK DESIGN TOPOLOGY SENSITIVITY ANALYSIS						
RELIABILITY COMPARISON MATRIX RESULT SUMMARY					SENSITIVITY ANALYSIS						
RELIABILITY	UNDERGROUND	OVERHEAD	HYBRID	RELIABILITY WEIGHTS	ALL EQUAL WEIGHTS		RANKING	TWO EQUAL WEIGHTS	RANKING		
UNDERGROUND	1	8.0689	7.0000	0.7772	RANKING 1	Underground	0.6483	Underground	0.5846		
OVERHEAD	0.1239	1	0.3333	0.0700	RANKING 2	Hybrid	0.2623	Hybrid	0.3237		
HYBRID	0.1430	3.0000	1	0.1528	RANKING 3	Overhead	0.0894	Overhead	0.0917		
CONSISTENCY RATIO (IN %)		8.85%									
SOCIAL / ENVIRONMENTAL COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY					FINAL NETWORK DESIGN TOPOLOGY RANKING						
SOCIAL / ENVIRONMENTAL COMPARISON MATRIX RESULT SUMMARY					FINAL TOPOLOGY RANKING SUMMARY						
SOCIAL/ENVIRONMENTAL	UNDERGROUND	OVERHEAD	HYBRID	SOCIAL/ENVIRONMENTAL WEIGHTS			RANKING				
UNDERGROUND	1	5.0000	3.0000	0.6370	RANKING 1	Underground	0.5975				
OVERHEAD	0.2000	1	0.3333	0.1047	RANKING 2	Hybrid	0.3140				
HYBRID	0.3330	3.0000	1	0.2582	RANKING 3	Overhead	0.0885				
CONSISTENCY RATIO (IN %)		3.31%									
RESET SHEET ALL DATA											

Figure 5-18: Case Study Electrification Network Design Topology Evaluation Model Results Summary

5.3.2.1 Load Estimation

The design ADMD as per City Power Johannesburg specification and guidelines was used in the evaluation model.

LOAD ESTIMATION

LOAD ESTIMATION RESULT SUMMARY

APPROACH

Supply Authority Standard

DESIGN ADMD

5.00 kVA

LOAD ESTIMATION

LOAD ESTIMATION

STATISTICAL / PROBABILISTIC

DETERMINISTIC

SUPPLY AUTHORITY STANDARD

LOAD ESTIMATION - SUPPLY AUTHORITY STANDARD

SUPPLY AUTHORITY STANDARD

ADMD

5

kVA

Next

Figure 5-19: Case Study Load Estimation Results

5.3.2.2 Network Design Topology Criteria Comparison Matrix

Our Client's preferences were to produce a cost-effective, reliable design which complies with the supply authority's standards and regulatory requirements. The initial matrix entries resulted in a consistency ratio greater than 10% and the improved matrix resulted in a consistency ratio of 4.42%.

NETWORK DESIGN TOPOLOGY COMPARISON MATRIX

Enter Comparison Matrix Entries (White Cells)

	Financial	Reliability	Social / Environmental
Financial	1	5	9
Reliability	0.200	1	5
Social / Environmental	0.111	0.200	1

Calculate Inverse Matrix Entries

Reset Matrix Entries

Check Consistency

Consistency Ratio: 0.1002

Calculate Criteria Weights

Financial	0.7352
Reliability	0.2067
Aesthetics / Social	0.0581

Improve Consistency - C

Improved Comparison Matrix

	Financial	Reliability	Social / Environmental	Improved Matrix Criteria Weights
Financial				
Reliability				
Social / Environmental				

Largest Check Matrix Entry:

Improved Consistency Ratio (Largest Entry Method):

Next

Microsoft Excel

Comparison Matrix Inconsistent (Consistency Ratio > 10%) - Proceed to Improve Consistency

OK

Figure 5-20: Case Study Inconsistent Network Design Topology Comparison Matrix

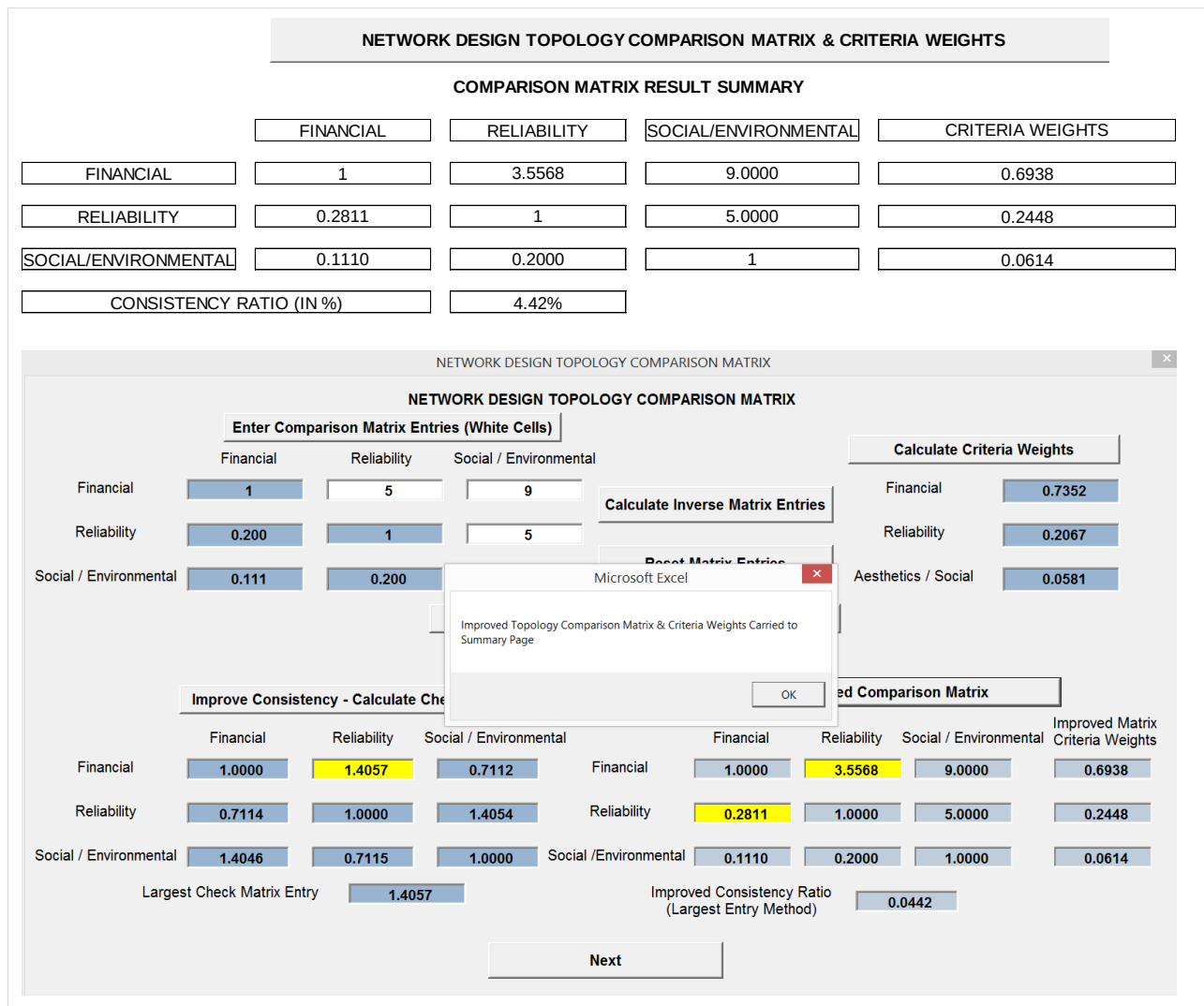


Figure 5-21: Case Study Improved Network Design Topology Comparison Matrix

5.3.2.3 Financial Comparison Matrix In Relation To Network Design Topology

Previous cost per stand of similar completed projects were used in the evaluation model with the life cycle cost component included, the average of each of the respective design topology options was used. The comparison matrix was initially inconsistent with a consistency ratio of 11.64% and the consistency had to be improved with the resultant consistency ratio of 5.07%.

FINANCIAL COMPARISON MATRIX

FINANCIAL COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY

Enter Comparison Matrix Entries (White Cells)

Financial	Underground	Overhead	Hybrid	Normalised Cost per Stand Vector	Capital Cost per Stand	LCC per Stand Over 20 Years
Underground	1	4.438	5	2.600	3	0.527
Overhead	0.225	1	0.195	0.2	0.594	23500
Hybrid	0.385	5.121	1	0.608	27750	66611.1

Consistency Ratio

0.1164

Check Consistency

Calculate Criteria Weights

Underground	0.5845
Overhead	0.0912
Hybrid	0.3243

Insert Cost per Stand @ Design ADMD

Calculate Inverse Matrix Entries

Reset Matrix Entries

Improve Consistency

Microsoft Excel

Comparison Matrix Inconsistent (Consistency Ratio > 10%) - Proceed to Improve Consistency

OK

Improved Comparison Matrix

	Underground	Overhead	Hybrid	Improved Matrix Criteria Weights
Underground				
Overhead				
Hybrid				

Largest Check Matrix Entry

Improved Consistency Ratio (Largest Entry Method)

Next

Figure 5-22: Case Study Inconsistent Financial Criteria Comparison Matrix in Relation to Network Design Topology

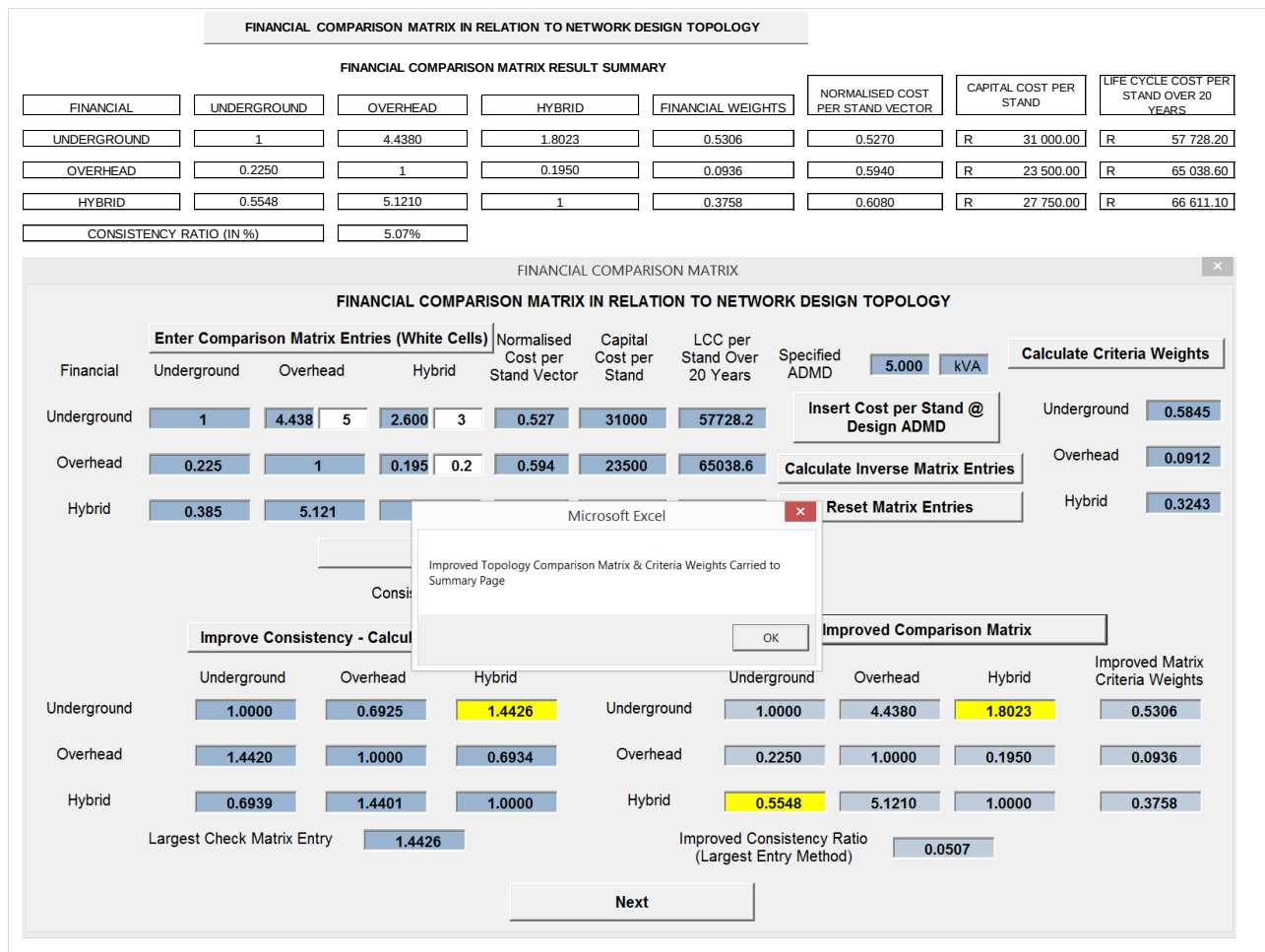


Figure 5-23: Case Study Consistent Financial Criteria Comparison Matrix in Relation to Network Design Topology

5.3.2.4 Reliability Comparison Matrix In Relation To Network Design Topology

Pair-wise comparison with respect to the reliability criteria for each of the design topology alternatives was performed. The comparison matrix was initially inconsistent with a consistency ratio of 20.1% and the improved consistency ratio was 8.85%.

RELIABILITY COMPARISON MATRIX

RELIABILITY COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY

Enter Comparison Matrix Entries (White Cells)

	Underground	Overhead	Hybrid
Underground	1	5	7
Overhead	0.200	1	0.3333
Hybrid	0.143	3.000	1

Calculate Inverse Matrix Entries

Reset Matrix Entries

Calculate Criteria Weights

Underground	0.7383
Overhead	0.0915
Hybrid	0.1702

Check Consistency

Consistency Ratio 0.2014

Improve Consistency - Calculate

	Underground	Overhead	Hybrid
Underground			
Overhead			
Hybrid			

Largest Check Matrix Entry

Improved Consistency Ratio (Largest Entry Method)

Next

Microsoft Excel

Comparison Matrix Inconsistent (Consistency Ratio > 10%) - Proceed to Improve Consistency

OK

ed Comparison Matrix

liability	Aesthetics / Social	Improved Matrix Criteria Weights

Figure 5-24: Case Study Inconsistent Reliability Criteria Comparison Matrix in Relation to Network Design Topology

RELIABILITY COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY

RELIABILITY COMPARISON MATRIX RESULT SUMMARY

RELIABILITY	UNDERGROUND	OVERHEAD	HYBRID	RELIABILITY WEIGHTS
UNDERGROUND	1	8.0689	7.0000	0.7772
OVERHEAD	0.1239	1	0.3333	0.0700
HYBRID	0.1430	3.0000	1	0.1528
CONSISTENCY RATIO (IN %)		8.85%		

RELIABILITY COMPARISON MATRIX

RELIABILITY COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY

Enter Comparison Matrix Entries (White Cells)

	Underground	Overhead	Hybrid
Underground	1	5	7
Overhead	0.200	1	0.3333
Hybrid	0.143	3.000	1

Calculate Inverse Matrix Entries

Reset Matrix Entries

Calculate Criteria Weights

Underground	0.7383
Overhead	0.0915
Hybrid	0.1702

Check Consistency

Improved Topology Comparison Matrix & Criteria Weights Carried to Summary Page

	Underground	Overhead	Hybrid	Underground	Overhead	Hybrid	Improved Matrix Criteria Weights
Underground	1.0000	0.6197	0.6200	0.689	7.0000	0.7772	
Overhead	1.6138	1.0000	0.6200	0.1239	1.0000	0.3333	0.0700
Hybrid	0.6203	1.6128	1.0000	0.1430	3.0000	1.0000	0.1528

Largest Check Matrix Entry

1.6138

Improved Consistency Ratio (Largest Entry Method)

0.0885

Next

Figure 5-25: Case Study Consistent Reliability Criteria Comparison Matrix in Relation to Network Design Topology

5.3.2.5 Social / Environmental Comparison Matrix In Relation To Network Design Topology

In order to comply with the regulatory requirements, the pair-wise comparison of the different network topology options was performed. The comparison matrix had a consistency ratio of 3.31% which is less than 10%.

SOCIAL / ENVIRONMENTAL COMPARISON MATRIX IN RELATION TO NETWORK DESIGN

SOCIAL / ENVIRONMENTAL COMPARISON MATRIX RESULT SUMMARY

SOCIAL/ENVIRONMENTAL	UNDERGROUND	OVERHEAD	HYBRID	SOCIAL/ENVIRONMENTAL WEIGHTS
UNDERGROUND	1	5.0000	3.0000	0.6370
OVERHEAD	0.2000	1	0.3333	0.1047
HYBRID	0.3330	3.0000	1	0.2582
CONSISTENCY RATIO (IN %)		3.31%		

SOCIAL / ENVIRONMENTAL COMPARISON MATRIX IN RELATION TO NETWORK DESIGN TOPOLOGY

Enter Comparison Matrix Entries (White Cells)

	Underground	Overhead	Hybrid
Underground	1	5	3
Overhead	0.200	1	0.3333
Hybrid	0.333	3.000	1

Check Consistency

Consistency Ratio 0.0331

Calculate Criteria Weights

Underground	0.6370
Overhead	0.1047
Hybrid	0.2582

Calculate Inverse Matrix Entries

Reset Matrix Entries

Improve Consistency - Calculate Ch

	Underground	Overhead	Hybrid
Underground			
Overhead			
Hybrid			

Largest Check Matrix Entry

Comparison Matrix

	Underground	Overhead	Hybrid	Improved Matrix Criteria Weights
Underground				
Overhead				
Hybrid				

Improved Consistency Ratio (Largest Entry Method)

Next

Microsoft Excel

Topology Comparison Matrix & Criteria Weights Carried to Summary Page

OK

Figure 5-26: Case Study Consistent Social / Environmental Criteria Comparison Matrix in Relation to Network Design Topology

5.3.2.6 Network Design Topology Performance Matrix

The performance matrix of the design topology criteria weights and each of the respective criterion weights in relation to the network design topology.

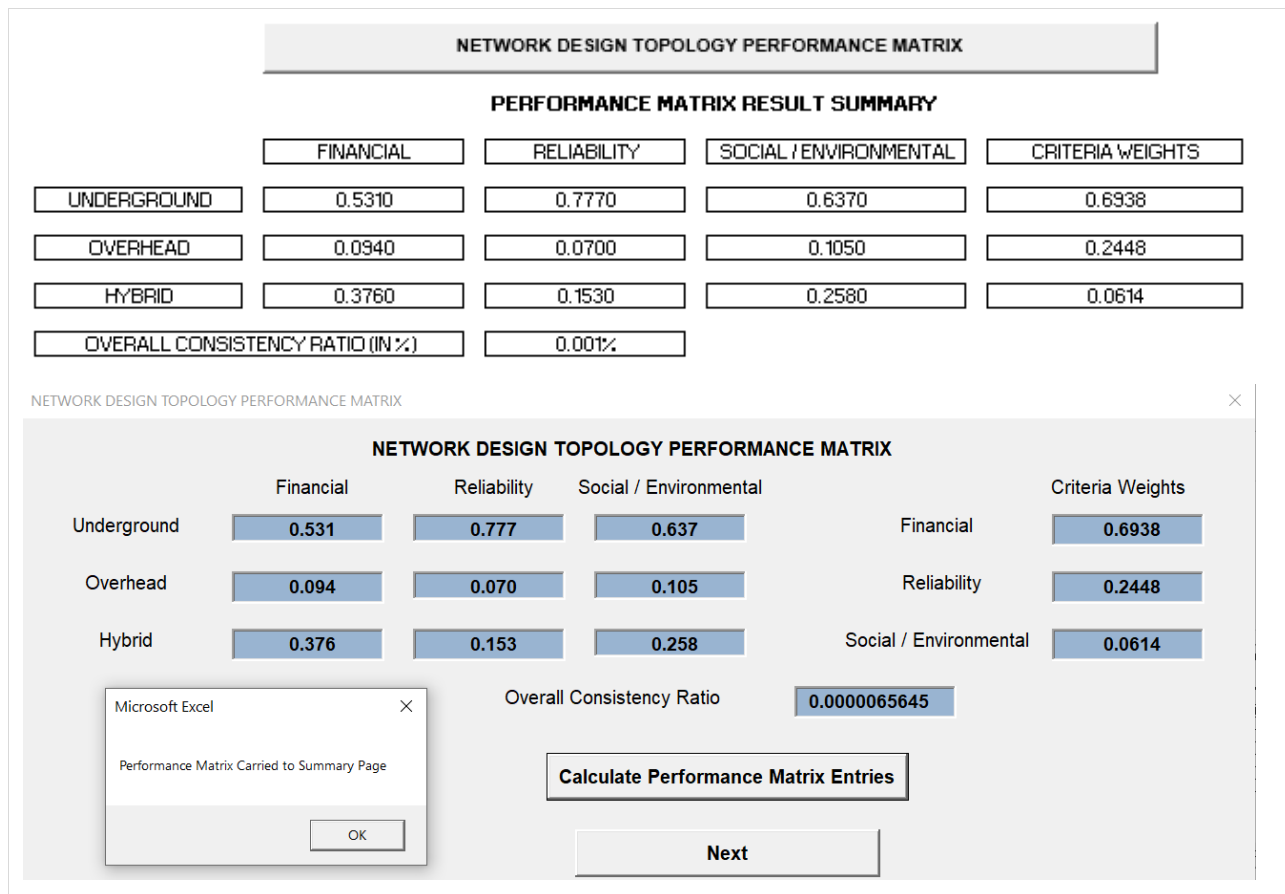


Figure 5-27: Case Study Network Design Topology Performance Matrix

5.3.2.7 Network Design Topology Ranking

The network design topology was ranked accordingly with the underground option being the highest ranked option.

NETWORK DESIGN TOPOLOGY RANKING

NETWORK TOPOLOGY RANKING RESULT SUMMARY

RANKING		
RANKING 1	Underground	0.5975
RANKING 2	Hybrid	0.3140
RANKING 3	Overhead	0.0885

NETWORK DESIGN TOPOLOGY RANKING

Ranking

Ranking 1	Underground	0.5975
Ranking 2	Hybrid	0.3140
Ranking 3	Overhead	0.0885

Calculate Topology Ranking

Next

Figure 5-28: Case Study Network Design Topology Ranking

5.3.2.8 Network Design Topology Ranking Sensitivity Analysis

A sensitivity analysis of the network design topology ranking for two scenarios of namely, network design topology of equal weights for the three criteria and highest criterion keeping its weights while the other two criteria being equal.

NETWORK DESIGN TOPOLOGY SENSITIVITY ANALYSIS

SENSITIVITY ANALYSIS

	ALL EQUAL WEIGHTS	RANKING	TWO EQUAL WEIGHTS	RANKING
RANKING 1	Underground	0.6483	Underground	0.5846
RANKING 2	Hybrid	0.2623	Hybrid	0.3237
RANKING 3	Overhead	0.0894	Overhead	0.0917

NETWORK DESIGN TOPOLOGY SENSITIVITY ANALYSIS
×

NETWORK DESIGN TOPOLOGY SENSITIVITY ANALYSIS

ALL EQUAL WEIGHTS

Ranking 1	Underground	0.6483	0.3333
Ranking 2	Hybrid	0.2623	0.3333
Ranking 3	Overhead	0.0894	0.3333

TWO EQUAL WEIGHTS

Ranking 1	Underground	0.5846	0.6938
Ranking 2	Hybrid	0.3237	0.1531
Ranking 3	Overhead	0.0917	0.1531

Calculate Topology Sensitivity Analysis - All Equal Weights

Calculate Topology Sensitivity Analysis - Two Equal Weights

Next

Figure 5-29: Case Study Network Design Topology Ranking Sensitivity Analysis

5.3.2.9 Network Design Topology Final Ranking

The final ranking of the network design topology model having taken into cognisance the sensitivity analysis.

FINAL NETWORK DESIGN TOPOLOGY RANKING

FINAL TOPOLOGY RANKING SUMMARY

		RANKING
RANKING 1	Underground	0.5975
RANKING 2	Hybrid	0.3140
RANKING 3	Overhead	0.0885

FINAL NETWORK DESIGN TOPOLOGY RANKING

FINAL NETWORK DESIGN TOPOLOGY RANKING

		Ranking
Ranking 1	Underground	0.5975
Ranking 2	Hybrid	0.3140
Ranking 3	Overhead	0.0885

Calculate Final Topology Ranking

Next

Figure 5-30: Case Study Network Design Topology Final Ranking

5.3.3 Validation

The input data used in the newly developed Microsoft Excel based evaluation model was used to validate the functionality of the model using the educational / commercial internationally used Super Decisions package.

The modelling of the input data of the case study is represented in Super Decisions as indicated in the figure below:

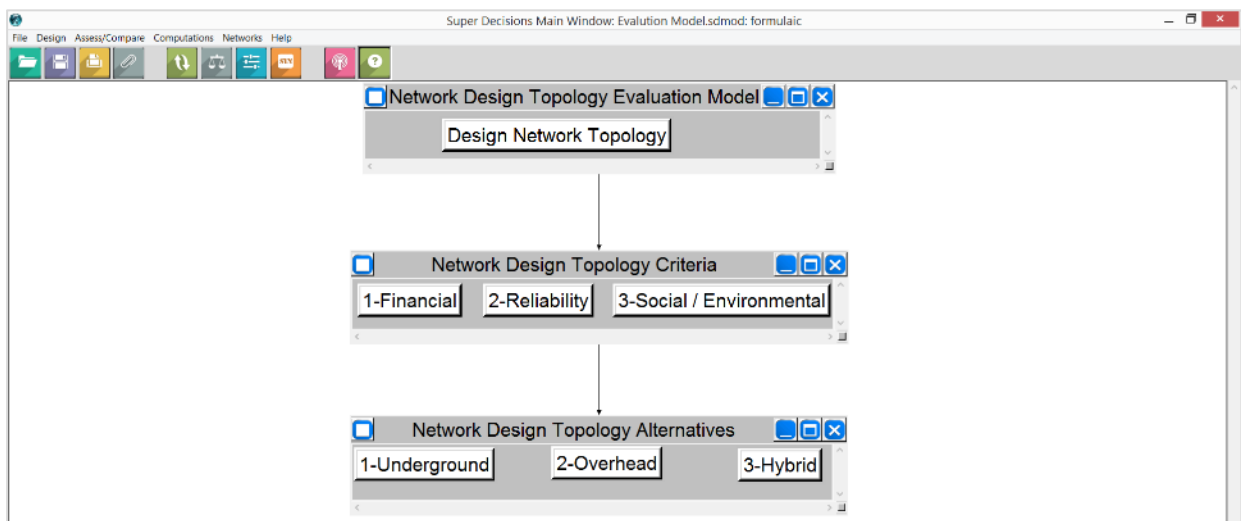


Figure 5-31: Case Study Electrification Network Design Topology Super Decisions Graphical User Interface (GUI)

The network design topology comparison matrix is modelled in the figure below:

1. Choose		2. Node comparisons with respect to Design Network Topol~		3. Results	
Node Cluster		Graphical Verbal Matrix Questionnaire Direct		Normal Hybrid	
Choose Node		Comparisons wrt "Design Network Topology" node in "Network Design Topology Criteria" c		Inconsistency: 0.06852	
Design Network~		2-Reliability is 5 times more important than 3-Social / Environmental		1-Financi~ 0.70852	
Cluster: Network Design ~		Inconsistency 2-Reliabil~ 3-Social / ~		2-Reliabi~ 0.23115	
Choose Cluster		1-Financi~ 4 9		3-Social ~ 0.06033	
Network Design~		2-Reliabil~ 5			
Restore		Copy to clipboard		Completed Comparison	
				Copy to clipboard	

Figure 5-32: Case Study Network Design Topology Comparison Matrix Super Decisions Results

This results in the underground network topology having more weight in terms of the financial criteria in comparison to the sum of the other two network topologies. The results of the financial criteria in relation to the network design topology alternatives as modelled on Super Decisions is represented in the figure below:

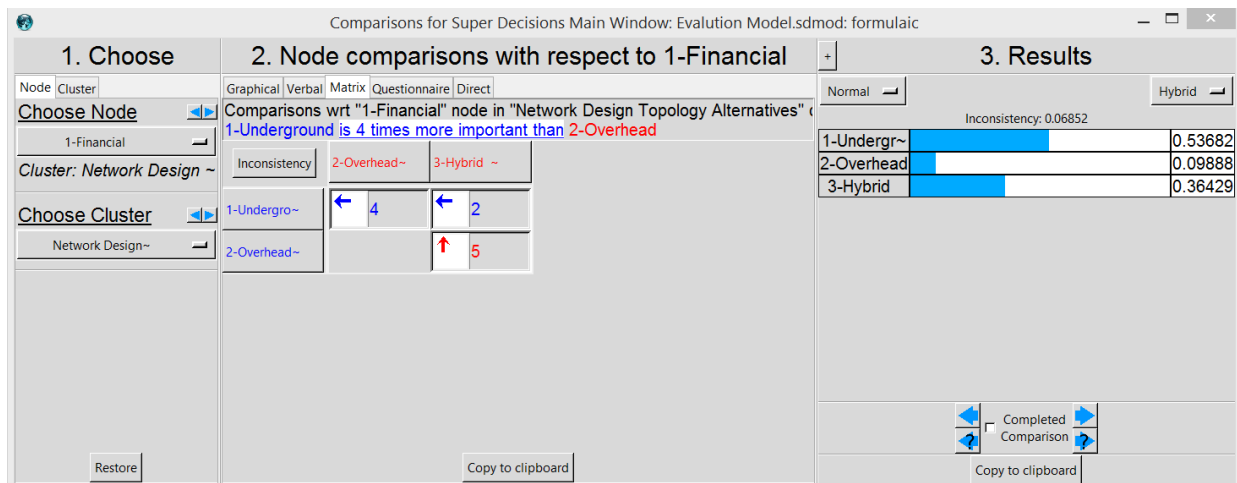


Figure 5-33: Case Study Financial Criteria Comparison Matrix in Relation to Network Design Topology Super Decisions Results

A similar case in terms of the reliability criteria, the underground network topology has significantly more weight. The results of the reliability criteria in relation to the network design topology alternatives as modelled on Super Decisions is represented in the figure below:

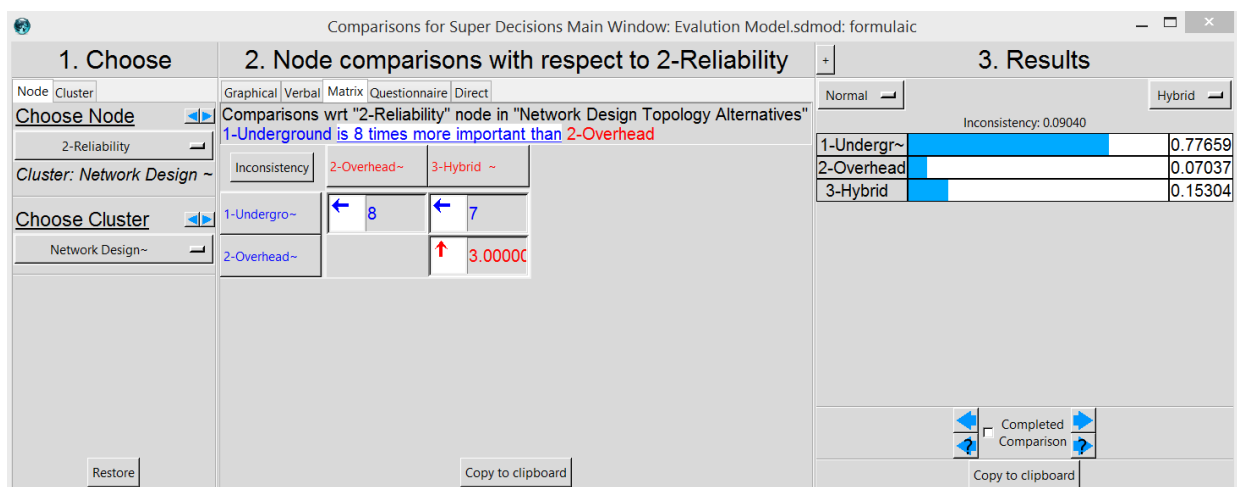


Figure 5-34: Case Study Reliability Criteria Comparison Matrix in Relation to Network Design Topology Super Decisions Results

The results provide a clear indication that the underground network topology has over two times more weight than the hybrid network topology on the social / environmental criteria. The results of the social / environmental criteria in relation to the network design topology alternatives as modelled on Super Decisions is represented in the figure below:

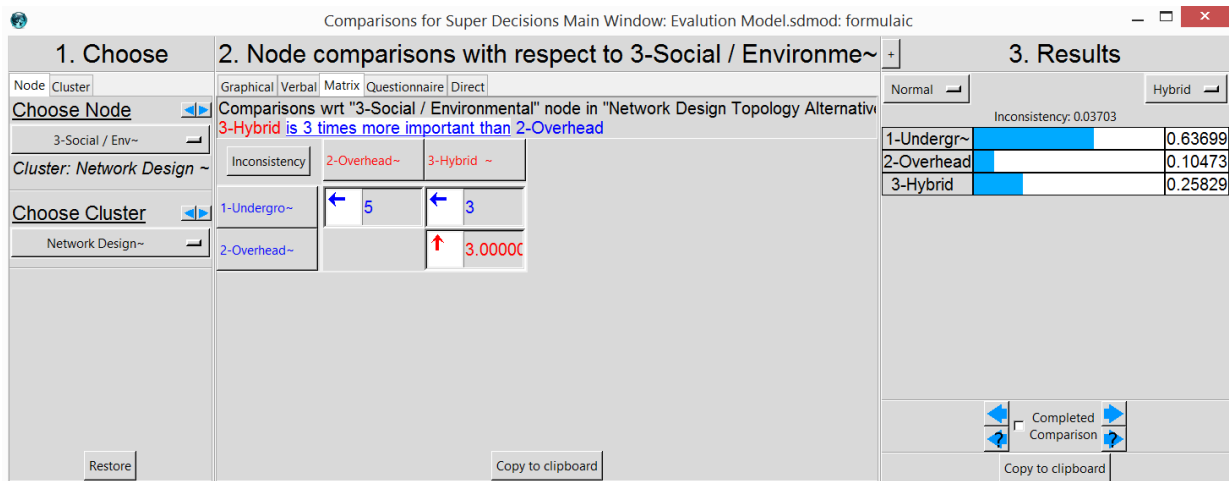


Figure 5-35: Case Study Social / Environmental Criteria Comparison Matrix in Relation to Network Design Topology Super Decisions Results

The ranking of the network design topology alternatives from Super Decisions is provided in the figure below:

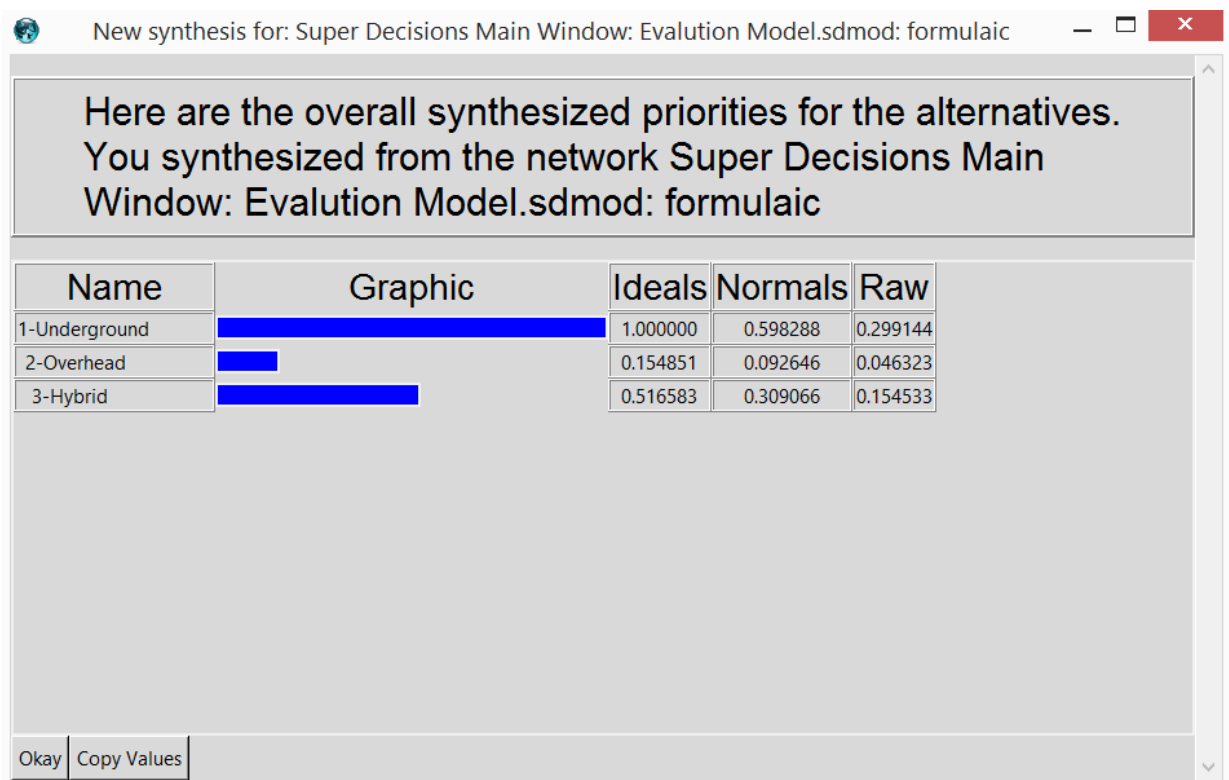


Figure 5-36: Case Study Ranking of Network Design Topology Super Decisions Results

5.4 ANALYSIS OF RESULTS

In the newly developed evaluation model, a decision on the network design topology can be obtained based on the fulfilment of the development load requirement, developer and / or supply authority preferences and requirements. The first point of departure in the evaluation model is the load requirement in which case the supply authority standard was implemented.

The newly developed model has the functionality to use not just whole number but also decimals between the limits of the fundamental scale of pair-wise comparisons between 1 and 9 together with the applicable inverses. In the newly developed model, the moment the consistency ratio is above the 10% threshold, the user is notified and model will proceed to improve the consistency ratio. In the event that the resultant “improved” comparison matrix is still above the 10% threshold, the user shall need to commence at the beginning with the pair-wise comparison.

In the model, only the social / environmental criterion in relation to the network design topology did not require a further iteration of an improved matrix to be calculated. Furthermore, it is worth noting that consistency index random sample for a matrix of an order of 3 applied by Super Decisions is ~0.529 in comparison to the random index 0.58 as applied in Section 4.3.3 of Chapter 4 in this dissertation.

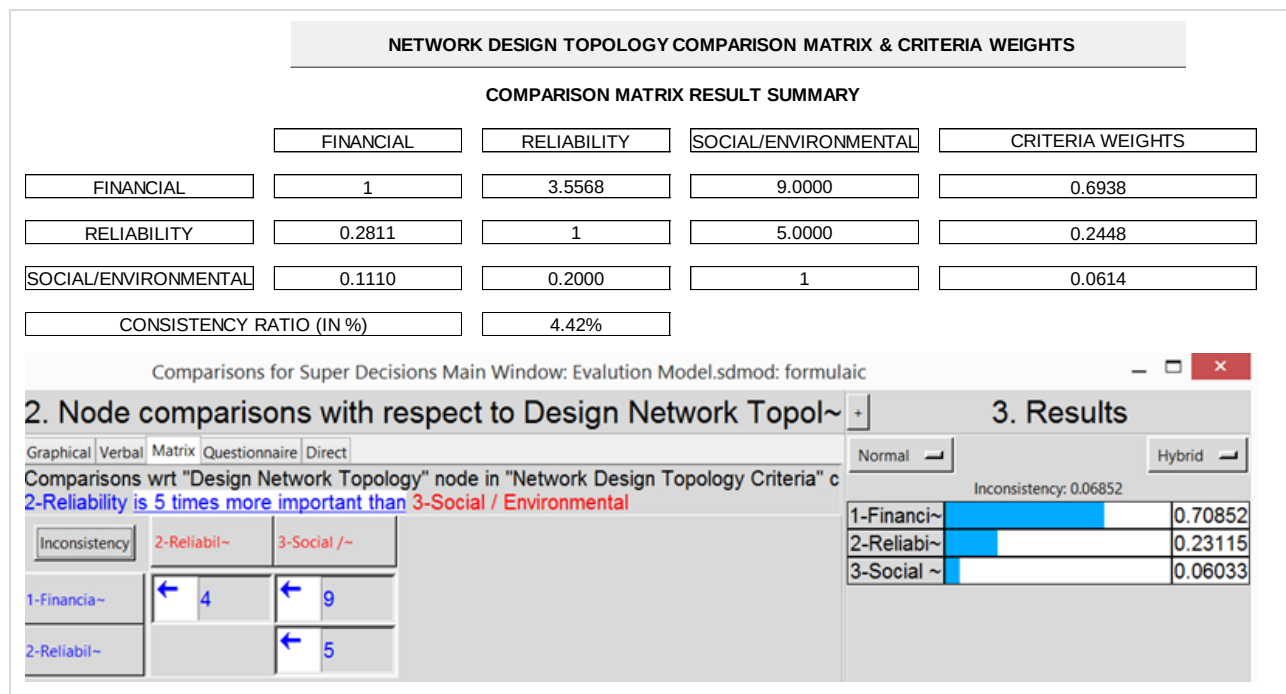


Figure 5-37: Comparison Network Design Topology Evaluation Model Results and Super Decisions Results

In the evaluation model, the actual costs of previous similar projects at the applicable ADMD are used in order to obtain a normalised column vector which reflects the applicable costs. In addition to that functionality, the life cycle cost of each network design topology alternative is included.

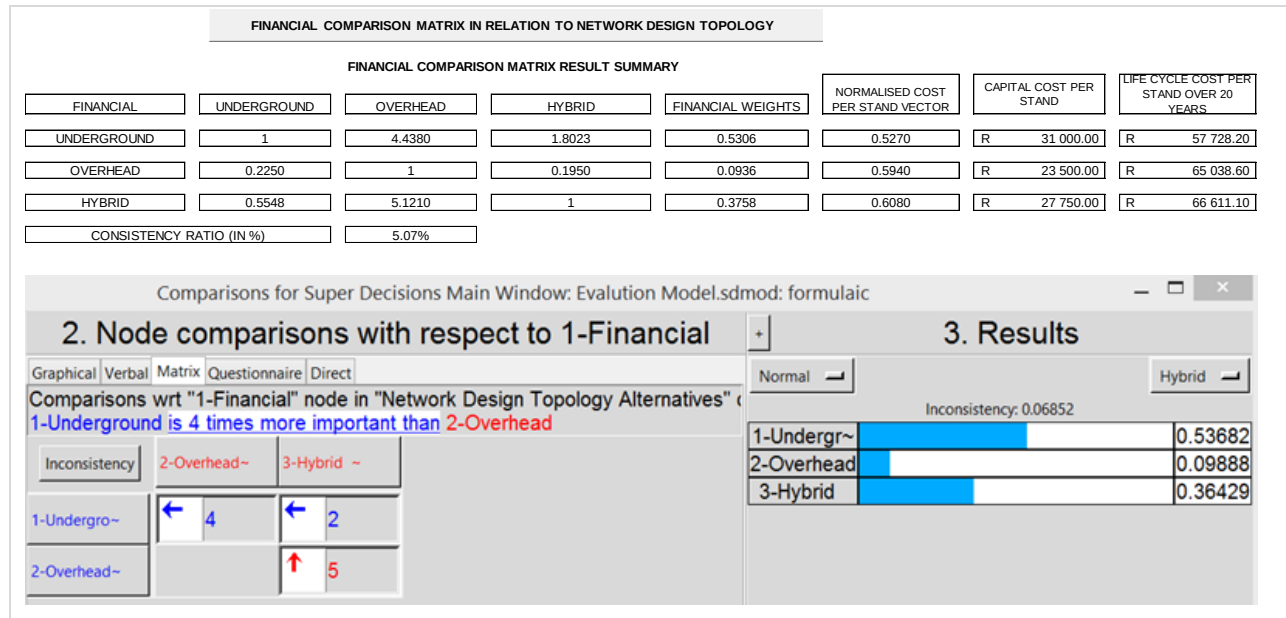


Figure 5-38: Financial Comparison Matrix In Relation To Network Design Topology Evaluation Model Results and Super Decisions Results

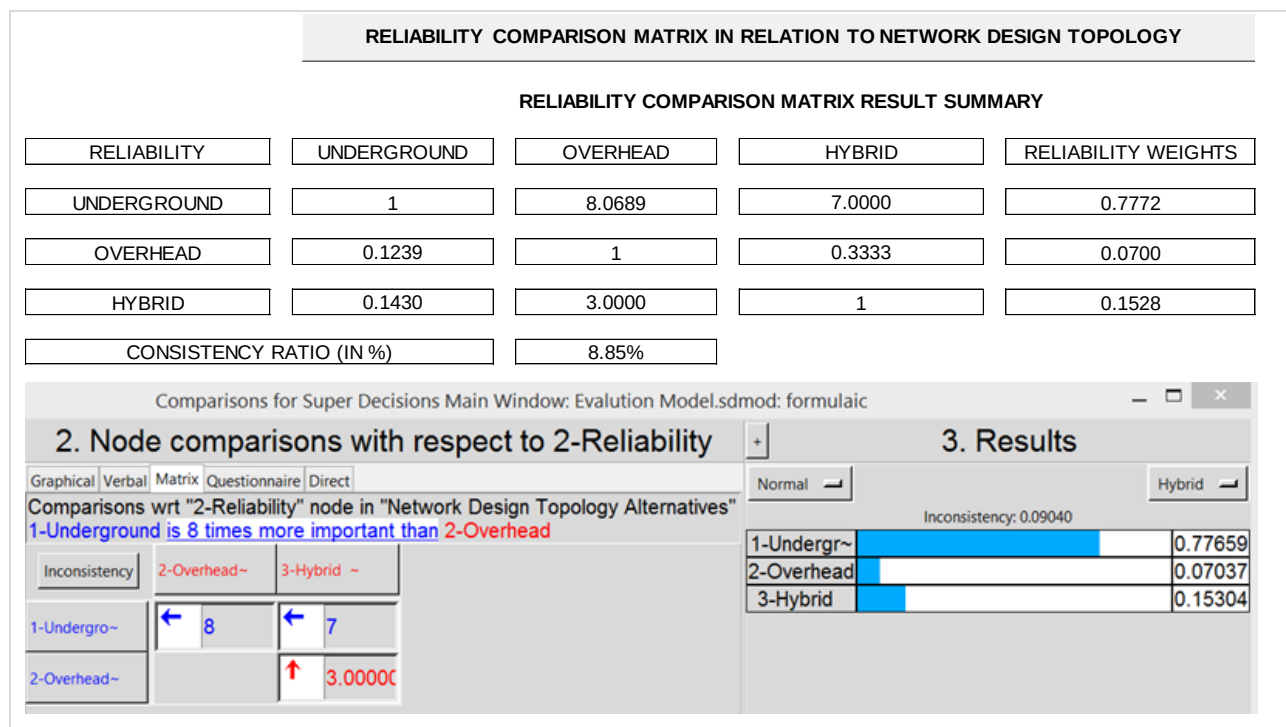


Figure 5-39: Reliability Comparison Matrix In Relation To Network Design Topology Evaluation Model Results and Super Decisions Results

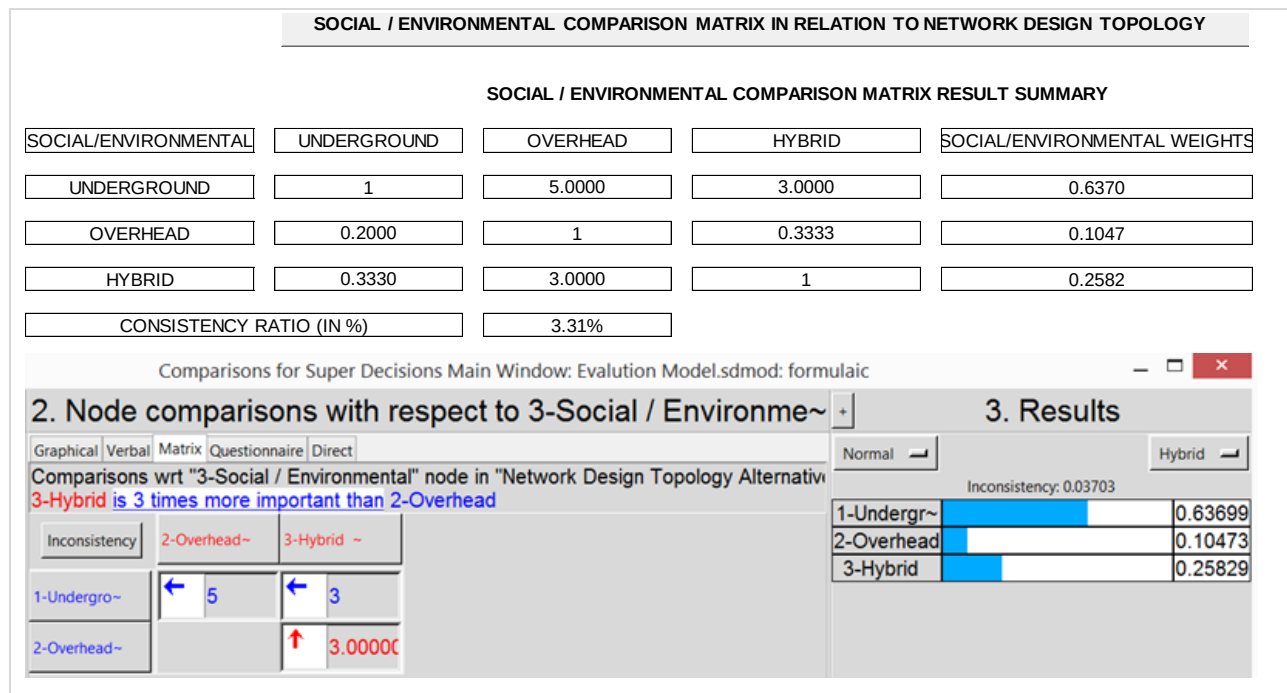


Figure 5-40: Social / Environmental Comparison Matrix In Relation To Network Design Topology Evaluation Model Results and Super Decisions Results

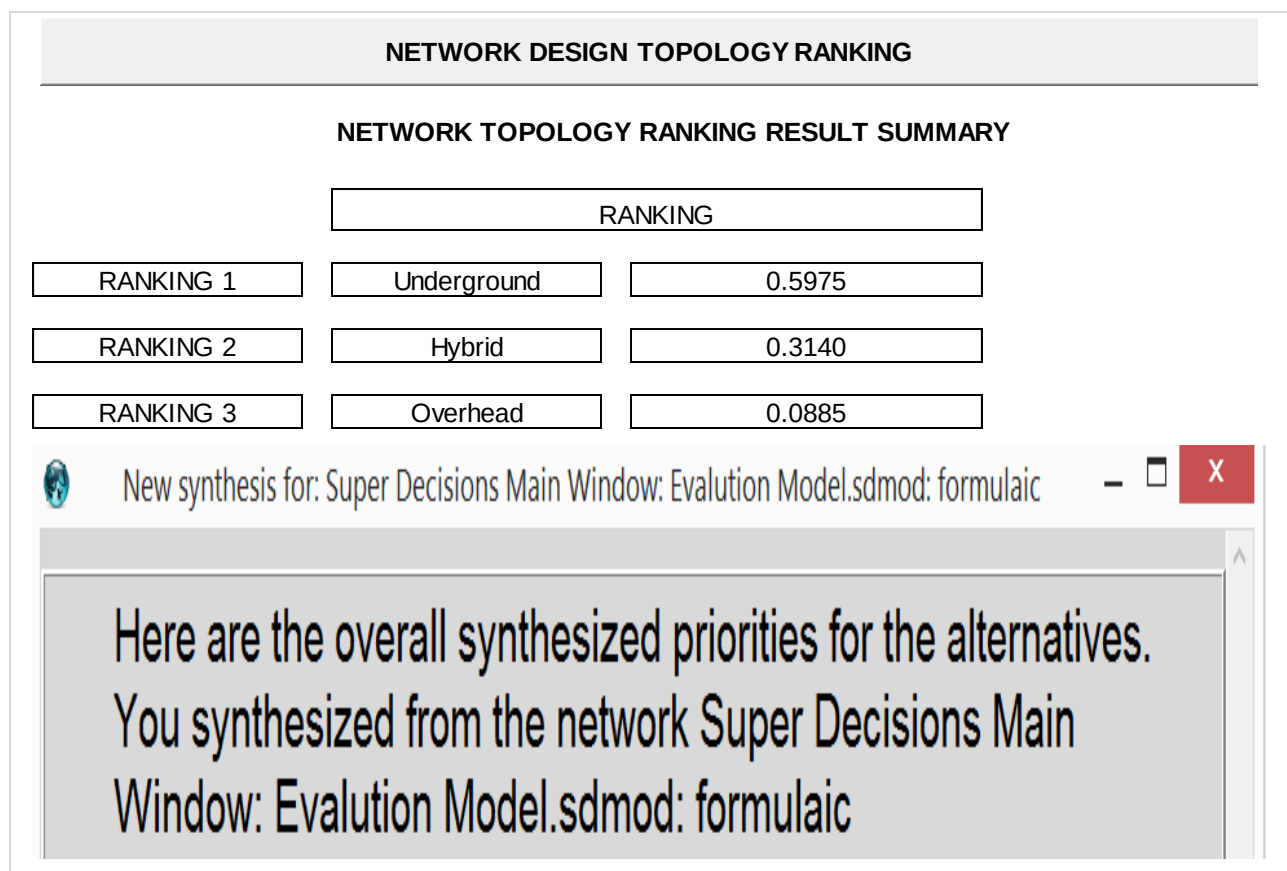


Figure 5-41: Ranking of Network Design Topology Evaluation Model Results and Super Decisions Results

The results comparison is summarised in the table below. The largest deviation in terms of the weights of the comparison matrix is in the network design topology matrix (5.88%) primarily due to the decimal characteristic of the evaluation model which Super Decisions does not possess. Essentially in the evaluation model we have comparison matrix entry financial-reliability (3.5568) with its inverse reliability-financial (0.2811) whereas the Super Decisions comparison matrix entry financial-reliability (4) with its inverse reliability-financial (0.25).

Description		Evaluation Model	Super Decisions	Absolute Deviation Percentage
Network Design Topology Comparison Matrix	Weights	0.6938	0.7085	2.07%
		0.2448	0.2312	5.88%
		0.0614	0.0603	1.82%
	Consistency Ratio	4.42%	6.85%	35.5%
Financial Comparison Matrix In Relation To Network Design Topology	Weights	0.5306	0.5368	1.15%
		0.0936	0.099	5.45%
		0.3758	0.3643	3.16%
	Consistency Ratio	5.07%	6.85%	26.0%
Reliability Comparison Matrix In Relation To Network Design Topology	Weights	0.7772	0.7766	0.08%
		0.0700	0.0704	0.57%
		0.1528	0.1530	0.13%
	Consistency Ratio	8.85%	9.04%	2.10%
Social / Environmental Comparison Matrix In Relation To Network Design Topology	Weights	0.6370	0.6370	0.00%
		0.1047	0.1047	0.00%
		0.2582	0.2583	0.04%
	Consistency Ratio	3.31%	3.70%	10.5%
Network Design Topology Ranking	Underground	0.5975	0.5983	0.13%
	Hybrid	0.3140	0.3091	1.59%
	Overhead	0.0885	0.0926	4.43%

Table 5-1: Deviation Analysis of the Evaluation Model Results and Super Decisions Results

This results in the absolute deviation highlighted in yellow above. In terms of the consistency ratio the largest deviation also occurred in the network design topology comparison matrix, as the input to the calculation of the consistency ratio, there is a larger deviation in the consistency ratio. It is worth noting that even though there is a large deviation, the resultant consistency ratio is still within the 10% threshold to consider the matrix consistent. In terms of the overall ranking results, the largest deviation was on the lowest ranked option which had an absolute deviation value of 4.43%. The resultant deviation did not have any significant influence on the overall ranking of the network design topology.

Even though the evaluation model has the required functionality to assist developers and / or supply authorities in deciding which network design topology to implement, there are a few shortcomings with regard to the evaluation model. The load estimation comparison functionality is not automated and the user will need to perform the check with the national minimum standards manually. The model does not have the ability to store historic project cost with the applicable design ADMD and the particular supply authority specification and / or requirement. It would be hugely beneficial to have such functionality as supply authority and / or developer specific evaluation would then be possible. Furthermore, different cost scenarios namely, low cost or high cost scenarios applicable to the supply authority and / or developer would then be possible.

An additional shortcoming of the evaluation model is the lack of use of actual reliability network data together with the social and environmental data. With the availability of network design topology specific reliability data, a more robust evaluation model will be possible as the evaluation model will then utilise actual data to ensure much more sustainable future residential electrification networks. This would be dictated by the supply authority and / or developer preferences subject to industry minimum requirements on the level of reliability required as well as the social and environmental requirements.

In the model, life cycle costing is included but the challenges around non-technical losses are not addressed. The challenge is more specifically for supply authorities rather than developers, in most cases, revenue collection is a huge priority in private developments resulting in actual collection of revenue and a bit of a challenge for supply authorities. At the end of the day, the core of all business is to be sustainable and profitable. The supply authority shall need to recover revenue and the evaluation model results will not be necessarily significant in the event that revenue control measures are not in place.

5.5 CHAPTER SUMMARY

In this chapter, the results of the evaluation model were presented. A systematic approach in which the finer details of the evaluation model were tabled and discussed. This commenced with the load estimation, criteria comparison matrix, criteria in relation to network design topology and the topology ranking. The evaluation model was then tested through a case study with the results of the model compared with those of educational / commercial package Super Decisions. An analysis of the results with the evaluation model shortcomings was discussed. In the final chapter of the dissertation, a conclusion together with possible future works and improvements on the evaluation model will be discussed.

CHAPTER 6

6. CONCLUSION

6.1 INTRODUCTION

In this final chapter of the dissertation a recap of what was covered and presented is discussed. The first chapter provided the problem statement together with the objectives – this was basically asking the question how do we decide which network design topology to implement in residential electrification networks. This also included a review of recorded literature undertaken by developed nations when considering whether to convert existing overhead electrical network to underground electrical networks. This then proceeded with a literature survey of the fundamental design planning factors which are used as input in the model. This not only considered the South African landscape, but it went further abroad into developed nations on their application of residential design planning.

In the third chapter, a thorough analysis of the three network design topologies was presented. This included a benefit analysis of the network design topologies and the glimpse synopsis of the status quo of the electrification design topology. In the fourth chapter, a brief account of things which could go wrong in electrification network design topology was discussed and the electrification network design topology evaluation model was derived through the implementation of the AHP. In the previous chapter, the electrification network design topology evaluation model was implemented through a case study and the results thereof presented. The model results were then validated and an analysis of the results performed.

This final chapter will seek to provide the conclusion of the dissertation by comparing the achieved model outcomes with the dissertation objectives as set out in the first chapter. Recommendation for possible future works which can be incorporated to improve and optimise the network design topology model shall be presented.

6.2 RESEARCH OUTCOMES

In Section 1.7, Chapter 1 of the dissertation the following items were set out as the deliverables and outcomes:

- A review and lessons learnt of how developed countries approach residential development electrification.

This particular outcome and deliverable was attained as a combination of a portion of Chapter 1 and the sections in Chapter 2. In terms of the lessons learnt with regard to residential electrification, this was covered as part of the literature review in Chapter 1 in which developed nations reviewing options of converting overhead electrical infrastructure to underground electrical infrastructure. This is an important lesson as residential electrification is a long-term investment exercise, thus infrastructure decisions need to be justifiable in order to avoid unnecessary and irrational future costs. An in-depth review of the current design practices and policy of developed nations with respect to residential network design topology was undertaken in Chapter 2. Developed nations supply authority's' design standards provide a clear guideline in terms the implementation of underground network design topology for residential developments in urban areas unless it is extremely uneconomical. Primary reasons for implementation of the underground network design topology in urban areas recorded by developed nations is reliability of the network and aesthetics associated with the network.

- An in-depth investigation and analysis of the different electrification design topologies.

This outcome and deliverable was achieved in Chapter 3 of the dissertation. In this chapter, a detailed analysis on the different network design topologies was undertaken. The design ADMD is critical in establishing the network design topology implemented. For residential developments with an ADMD of 2kVA and lower, an overhead network design topology is ideal to service such developments. On the extreme side, residential developments with an ADMD above 5kVA, an underground network design topology is ideal to service developments in this category. The residential developments which have an ADMD between 2kVA and 5kVA present a set of choices in which the different network design topologies are viable depending on the supply authority and / or developer requirements.

- A Microsoft Excel based network design topology evaluation model with the objective of aiding the supply authority or developer in taking an informed and sustainable decision on the network design topology to be implemented.

The network design topology evaluation model was developed in Chapter 4 with the model tested in a case study in Chapter 5 of the dissertation. The evaluation model fundamental base is the design ADMD. Furthermore, the fundamental base is incorporated with the application of actual costs of previous similar projects of the same ADMD, reliability and the social / environmental criteria. The financial component also makes provision for life cycle costing which is of outmost importance primarily to the supply authorities in order to make rational network topology decisions.

Based on the pair-wise comparison of the AHP for the different criteria and the network design topology, the available network design topologies are ranked accordingly to provide the most suitable residential network topology to be implemented.

6.3 RECOMMENDATIONS AND FUTURE WORK

The model is a tool developed for use in the consulting environment which aims to assist our Clients who are mainly developers and supply authorities in deciding which network design topology to be implemented in residential electrification. The evaluation model is a first of its kind in which network design topologies are evaluated prior implementation. The first major milestone of having a functional model has been achieved, there are some items which can be done to significantly improve the overall evaluation model. The first item of having the previous project costs in a database which can be arranged according to various criteria namely, per design ADMD, per year and per supply authority. With this database, the user can then have different options of how the cost can be represented, either averaged over a particular period, lower or higher distribution and a specific base year. This will then only require the database to be updated as and when required, but the recommended period would be annually. This would result in an improved evaluation model as an automated functionality would be added to the evaluation model. The inclusion of the automated feature for the comparison of the load estimation with regard to minimal national standards would be beneficial in the evaluation model.

The development of smart cities will make it possible to be able to retrieve reliability data per network design topology and not only as it current is on the entire supply authority network infrastructure. The annual reliability data can also be transferred to a database which can be linked with the evaluation model to improve the performance of the network design topology evaluation model. Considering the progression and developments in the field of smart cities, this functionality will also then be achieved with less human interaction for the input data as it can be all automated into the database. This will then result in actual reliability data being a variable and being used in deciding which network design topology to implement.

Another factor which can be improved is the social / environmental criterion. This will still require significant amount of work in order to attain the definitive quantitative correlation between the specific impacts of the network design topology to the social / environmental criterion. With all these possible improvements incorporated into the evaluation model, the user can then also be able to indicate the number of units to be serviced in the particular development in order to be able to present the estimated project cost with a high degree of certainty. The ultimate role of the design topology evaluation model is to have it incorporated as a component in electrification design software.

In this way, the design package would then consist of how the decision to implement a particular network topology was achieved and the subsequent design of the preferred network topology.

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APPENDIX – SOURCE CODE

The entire model is developed in Microsoft Excel using the built developer function and utilises macros in Microsoft Excel (Visual Basic for Applications) VBA.

Note:

The source code consists of 10 Microsoft Excel VBA modules, 14 Microsoft Excel VBA userforms with 4 929 lines of code. This translates to approximately 79 A4 pages. This entire source code is available on request from the author.

LoadEstimationForm

```
Private Sub RunDeterministicApproach_Click()  
Unload LoadEstimationForm  
Sheet1.Activate  
Cells(13, 21) = "Deterministic"  
MsgBox ("Design Approach Carried to Summary Page")  
DeterministicForm.Show  
End Sub
```

```
Private Sub RunStatisticalApproach_Click()  
Unload LoadEstimationForm  
Sheet1.Activate  
Cells(13, 21) = "Statistical / Probalistic"  
MsgBox ("Design Approach Carried to Summary Page")  
StatisticalForm.Show  
End Sub
```

```
Private Sub RunSupplyAuthouritySTD_Click()  
Unload LoadEstimationForm  
Sheet1.Activate  
Cells(13, 21) = "Supply Authourity Standard"  
MsgBox ("Design Approach Carried to Summary Page")  
SupplyAuthourityForm.Show  
End Sub
```

StatisticalForm

```
Private Sub CalcADMDStatistical_Click()  
StatisticalADMDValue = (Val(AlphaValue) / (Val(AlphaValue) + Val(BetaValue))) * Val(CBValue) * 0.23  
End Sub
```

```
Private Sub NextStepStatistical_Click()  
Call CalcADMDStatistical_Click  
Sheet1.Activate  
Cells(16, 21) = Val(StatisticalADMDValue)  
MsgBox ("Design ADMD Value Carried to Summary Page")  
StatisticalForm.Hide  
End Sub
```

```
Private Sub ResetADMDStatistical_Click()  
Unload StatisticalForm  
StatisticalForm.Show  
End Sub
```

DeterministicForm

```

Private Sub CalcDwellingDiversifiedLoad_Click()
If FloorAreaValue.Value < 100 Then
    DiversifiedLoadSocketOutletsValue = (((Val(FloorAreaValue) / 100) * 5000) * 0.5) / 1000
Else
    DiversifiedLoadSocketOutletsValue = ((5000 + ((Val(FloorAreaValue) / 100) - 1) * 1000) * 0.5) / 1000
End If
DiversifiedLoadLightingValue = Val(ConnectedLoadLightingValue) * 0.5
DiversifiedLoadWaterHeatingValue = Val(ConnectedLoadWaterHeatingValue) * 1
DiversifiedLoadMotorValue = Val(ConnectedLoadMotorValue) * 1
DiversifiedLoadCookingValue = Val(ConnectedLoadCookingValue) * 0.5
DiversifiedLoadSpaceHeatingValue = Val(ConnectedLoadSpaceHeatingValue) * 1
DwellingDiversifiedLoadValue = Val(DiversifiedLoadSocketOutletsValue) +
Val(DiversifiedLoadLightingValue) + Val(DiversifiedLoadWaterHeatingValue) +
Val(DiversifiedLoadMotorValue) + Val(DiversifiedLoadCookingValue) +
Val(DiversifiedLoadSpaceHeatingValue)
End Sub

Private Sub CalcADMDDeterministic_Click()
If (DCFListBox.Value = "AMEU" And LoadControlListBox.Value = "Yes") Then
    DeterministicADMDDValue = (Val(DwellingDiversifiedLoadValue) -
Val(DiversifiedLoadWaterHeatingValue)) / (1 + (2 / 1))
Else
    If (DCFListBox.Value = "AMEU" And LoadControlListBox.Value = "No") Then
        DeterministicADMDDValue = (Val(DwellingDiversifiedLoadValue)) / (1 + (2 / 1))
    End If
End If
If (DCFListBox.Value = "Custom") Then
    Dim textbox, addition, division, space, definition, equal As String
    addition = chr(43)
    division = chr(47)
    space = chr(32)
    equal = chr(61)
    definition = "DCF"
    DCFSelected = definition + space + equal + space + TextBox16 + space + addition + space + TextBox20
    + division + TextBox18
Else
    If (DCFListBox.Value = "AMEU") Then
        TextBox16 = "1"
        TextBox20 = "2"
        TextBox18 = "n"
        definition = "DCF"
        equal = chr(61)
        addition = chr(43)
        division = chr(47)
        space = chr(32)
        equal = chr(61)
        DCFSelected = definition + space + equal + space + TextBox16 + space + addition + space + TextBox20
        + division + TextBox18
    End If
End If

If (DCFListBox.Value = "Custom" And LoadControlListBox.Value = "Yes") Then
    DeterministicADMDDValue = (Val(DwellingDiversifiedLoadValue) -
Val(DiversifiedLoadWaterHeatingValue)) / (Val(TextBox16) + (Val(TextBox20) / 1))
Else
    If (DCFListBox.Value = "Custom" And LoadControlListBox.Value = "No") Then
        DeterministicADMDDValue = (Val(DwellingDiversifiedLoadValue)) / (Val(TextBox16) + (Val(TextBox20) /
1))
    End If
End If

```

```

End If
End If
Sheet1.Activate
Cells(16, 21) = Val(DeterministicADMDValue)
End Sub

Private Sub DeterministicADMDValue_Change()
DeterministicADMDValue = Val(DeterministicADMDValue)
End Sub

Private Sub NextStepDeterministic_Click()
Call CalcADMDDeterministic_Click
Sheet1.Activate
Cells(16, 21) = Val(DeterministicADMDValue)
MsgBox ("Design ADMD Value Carried to Summary Page")
DeterministicForm.Hide
End Sub

Private Sub ResetADMDDeterministic_Click()
Unload DeterministicForm
DeterministicForm.Show
End Sub

```

SupplyAuthourityForm

```

Private Sub NextStepSupplyAuthouritySTD_Click()
SupplyAuthouritySTDADMDValue = Val(SupplyAuthouritySTDADMDValue)
Sheet1.Activate
Cells(16, 21) = Val(SupplyAuthouritySTDADMDValue)
MsgBox ("Design ADMD Value Carried to Summary Page")
SupplyAuthourityForm.Hide
End Sub

```