203

OPTIMAL NETWORK STRUCTURE IN AN OPEN MARKET ENVIRONMENT

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Optimal Network Structure in an Open Market Environment

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Executive Summary

This is the final report of the CIGRE Task Force 38-05-10 "Optimal Network Structure in an Open Market Environment". The work of the task force started in May 1998 and finished in November 2001.

The focus of the report is on network planning in the "new environment" of a liberalised electricity market. The development of the network is viewed from different stakeholders' objectives. The stakeholders in the transmission network are groups or individuals who have a stake in, or an expectation of, the development and performance of the network.

An open network exists when all market players meet equal admission rights and obligations. This requires that the grid be administered through a transparent set of rules such as a grid code. This and other definitions are given in Chapter two.

One of the effects of market liberalisation is the unbundling of roles within the electricity supply industry. In Chapter three new stakeholders are described, and grouped into four principal role categories:

- Those who manage the transmission networks
- Those who use the networks to trade
- Those who facilitate energy trading
- Statutory Authorities

The major stakeholders, identified as the demand customers, power producers, system operator, network owners, and regulator, exert new and different driving forces, while the long-standing driving forces have reduced in importance. The effects of the new driving forces upon the planning process are studied

Since development priorities and interactions involved in decision-making are between real persons and interest groups, it is impossible to predict with certainty that a solution will satisfy all stakeholders. Competition and customer choice has the effect of increasing the uncertainty that a planner must deal with. In this new dynamic environment, the planner needs to consider more flexible approaches to modelling and developing the network. In Chapter four scenario modelling is proposed for decision-making to cope with the conflicting interests of different stakeholders, and thus to achieve an "optimal" development of the network.

To demonstrate some of the qualities of using scenario modelling, a planning exercise on a small three-bus test system is carried out in Chapter five.

Many of these "new" optimisation methods are not used in transmission planning yet, and few software packages adopt them. Nonetheless their concepts seem to align with both social and business objectives and are thus becoming more familiar. The methods described do not claim to provide a unique "best" solution by rigorous mathematical modelling, and multi-criteria optimisation and decision under uncertainty methods have both advantages and disadvantages. It follows that to gain acceptance, careful consideration will need to be given to how to explain pseudo-optimisation methods and tools to a range of stakeholders.

CONTENTS

1 INTRODUCTION

Background of the task force
To investigate the impact of open trading on power system development Study Committee 38 established Task Force 38-05-10 on “Optimal network structure in an open market environment” in December 1997.

Before the liberalisation process of the electricity sector started, the main driving forces for network development were:
- Increase of demand
- Connection of new power stations, built to meet the demand
- High reliability of the network

The cost incurred to develop the network was borne by the customers. Some consequences of this practice were that reliability and voltage quality increased continuously, the technical complexity of the networks gradually increased by use of the latest technology components, and the economic point of view was of less importance. This resulted in cost intensive networks that were designed to cope with extreme outage conditions with very low probability of occurrence.

After liberalisation (deregulation) the electricity industry went through several changes both in organisation structure, attitude to cost, and relationship with customers. Some examples are given below:
- Roles are separated with different ownership or control
- The power producers are organised for competition
- The transmission companies have become natural monopolies
- The consumers can shop around for cheap power and good service
- Investments in new technology must result in increased profit or reduced cost even in the short term thinking

The new situation for the network owners has resulted in changes of the planning procedures with emphasis put on economic considerations, and less room for technological extravagance.

Scope of work for the task force:
- Investigate topics related to open transmission networks in competitive market environments
- Discuss what are the driving forces, and what impacts these will have on the utilisation and development of future transmission networks
- Analyse how optimisation techniques can be used to define structures and components needed to handle variable transport requirements at defined levels of security

Possible tools to solve these problems optimally, and the impact on planning and operating procedures, should be examined.

2 DEFINITIONS AND EXPLANATION

2.1 GENERAL DEFINITIONS

Transmission Network

A transmission network is a system of high voltage electric circuits provided for the purposes of the transmission of electricity, to link energy sources together and to deliver energy to major load blocks. A distinction is made between:

- backbone or horizontal networks [1], which are influenced by changes in inter or intra-country boundary exchanges.
- local supply or vertical networks[1] which connect generation and load to the horizontal network.

Transmission Capacity

The Capacity of a transmission system is best expressed as a nodal quantification of its ability to deliver electrical energy [2]. The estimation of capacity concerns the ability of circuits to carry load current, maintain voltage regulation and the capability of devices to make, carry and interrupt fault current. The system should also remain stable when operated within its capacity limits.

Capacity could be assessed as a total nodal transfer capability with all network branches and equipment in service, or it could be assessed as a firm capacity. Firm Capacity is preferred as it is closer to the System Operator's ability to load the system.

Stakeholders

The stakeholders in the transmission network are groups or individuals who have a stake in, or an expectation of, the development and performance of the network. They include those directly involved in the management of the grid, managers of the power exchanges, which rely on the network, the users of the network and the regulatory authorities and others affected by network development.

Open network

An open network exists when all market players have equal admission rights and obligations.

2.2 REQUIREMENTS OF AN OPEN NETWORK

Open

An open network requires that the grid be administered through a transparent set of rules such as a grid code. Normally these rules have to be endorsed by law.

Markets that allow negotiated third party access are not open, because each market player negotiates conditions for access bilaterally with the grid owner. By definition the conditions will be confidential and so in conflict with the demand for a transparent grid code

Efficient
A network, though open, may not be utilised efficiently. Network efficiency is achieved when trading of physical energy is only constrained by physical network limitations.[1]

If transmission channels are bought independently of physical energy exchange, the holder may exhibit monopolistic behaviour. For instance, if a generator buys the priority rights on transmission capacity between his area and another on a long-term contract, he can use the capacity for preventing generators in the other area from competing in his area. In this example, the network is not being used efficiently, as the transmission priority rights increase costs for buyers and/or reduce income for the other sellers in the power market.

Therefore to achieve efficiency, all unused transmission capacity must be made available to the market for trading.

Optimal
Network efficiency only indicates that the transmission capacity is used, but not whether the resources are allocated in an optimal way. If transmission constraints exist, the optimal point exists within the efficiency region. The relations are described in the illustration below.

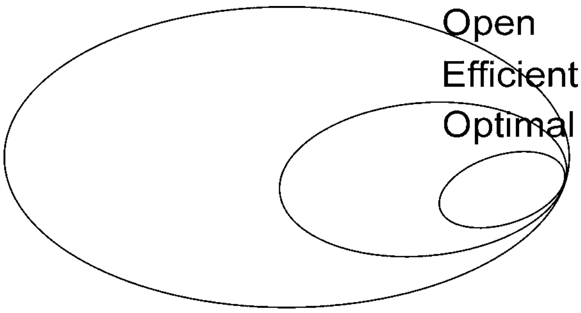

Figure 2.1 Regions for open, efficient and optimal network when transmission constraints exist.

3 OPEN NETWORK DEVELOPMENT

3.1 STAKEHOLDERS IN THE NETWORK

One of the effects of market liberalisation is the unbundling of roles within the electricity supply industry, particularly those formerly performed by the traditional utility. Those responsible for each role may have a different interest in, or expectation of the performance and development of the transmission system. Each is therefore a stakeholder in the network. These new stakeholders are grouped into principal role categories in table 3.1. It should be noted that administration arrangements in different countries or states could lead to parties performing more than one of these roles.

[1] Please note the relation to the definition normally used in Economics: "Efficiency is achieved when it is not possible to produce more of one good without producing less of some other good.", [Economics, Parkin, Powell, Matthews]

Table 3.1 Main Stakeholder Groups

Those who manage the transmission networks	Those who use the networks to trade	Those who facilitate energy trading	Statutory Authorities
- Transmission Administrator - System Operator - Network Owner - Measurement and Metering Administrator	- Demand Customer - Power Producer	- Market Operator - Energy Retailer - Energy Trader - Power Broker	- Electricity Regulator - Other Public Authorities

Separation of the roles leads to greater administration and inter-organisational dealings and may lead to duplication of effort and resources. However, it does have the advantage of providing clear focus for each new organisation in pursuit of its objective. In addition, the interface between the parties carrying out the roles is more formal and transparent, which should, but may not necessarily result in greater efficiency.

In the following sections, each of these roles is described, and then summarised in table 3.2 at the end of this section.

3.1.1 Stakeholders who manage the transmission network

Figure 3.1 illustrates how the different management roles relate to each other. Each system has one system operator, and one or more transmission administrator. The transmission administrator can administer a region serviced by several network owners. (Although the market operator does not perform a network management role, it is included in Figure 3.1 to show how this role relates to the management roles.)

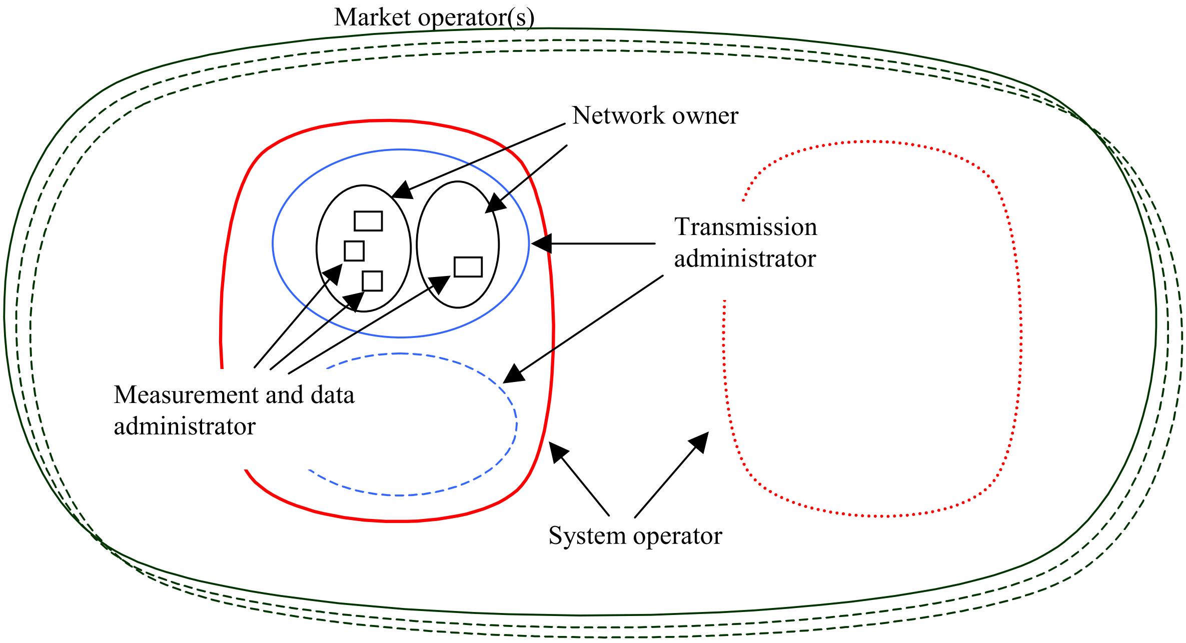

Figure 3.1 The management roles and their relation to each other

No standard market structure has evolved for the deployment of these management roles. In some markets, roles are combined in the one organisation. For instance, in England and Wales the system operator, transmission administrator, network owner, market operator and metering administrator roles are carried out by one body. One of the Canadian provinces, on the other hand, has a separate system operator, transmission administrator, and network owners.

3.1.1.1 System Operator

The system operator controls the power system, to achieve satisfactory power balance in real time, and safety, security, quality and reliability of the system.

The system operator may alter generator schedules to maintain the power balance and manage constraints and congestion. The operator is in control of all system switching for scheduled and emergency outages, although the network owners may do the actual switching.

3.1.1.2 Transmission Administrator

The Transmission Administrator (TA) is responsible for the overall co-ordination of the transmission system. The TA is charged with the planning and development of the network, including provision of access to the power system for all parties in a non-discriminatory manner.

The TA role is often combined with either the system operator role or the network owner role. In a large market, separating the TA role from system operation allows greater focus on regional development and network pricing, where each region would have its own TA. For example, in Australia, operation of the Australian power system is carried out centrally, while each state retains the transmission administration role. This allows the states to develop their own networks, and set their own tariffs. Transmission planning by an independent transmission administrator also offers less development bias towards the interests of a network owner or system operator in an open market.

3.1.1.3 Network Owner

The network owner is the owner of the assets comprising the transmission network, including interconnectors. Power is transported from producer to demand customer over these assets. In many cases, such as in Germany, there are multiple owners, each owning the assets in its existing geographical area of operation. Multiple ownership within a franchise area may arise in the future, where reinforcements are made open to tender.

3.1.1.4 Measurement and Data Administrator

The Measurement and Data Administrator obtains metered data on power and energy exchanges, together with any other relevant parameters for use by the market participants to permit efficient settlement, with minimum disputes. This role could be carried out by multiple meter operators.

The measurement and data administrator has no direct role in network development, other than in the planning of metering points.

3.1.2 Users of the Transmission Network

The second category of stakeholders, with an interest in network development, are those who use the transmission network to trade in energy. The users are the demand customers and power producers. Demand customers take electrical power from the network, whereas power producers deliver electrical power into the network and are substantial providers of ancillary services.

It should be noted that while users may normally play one of the above roles, they might change roles under certain circumstances. For instance, Power Producers become demand customers, when they take power from the grid to start up plant. Customers, with CHP plant can become Power Producers, when they export to the system. Both power producers and demand customers can play the role of energy retailers.

3.1.3 Trade Facilitators

Industry deregulation has led to a break-up of electricity supply monopolies, and the establishment of new markets allowing competition in customer supply. New players have entered the industry or been established to facilitate trade between power producers and demand customers.

3.1.3.1 Market operators

The role of the market operators are to promote efficient competition in the energy market leading to economic scheduling/dispatch, and develop products that match the needs of the market participants. These products should facilitate

- Trade of energy
- Exploitation of natural resources, both in short and long time horizon
- Economic risk management for the players in the market (Price hedging)

There are two types of market operators:

- Power exchanges that operate the organised markets
- Power brokers that operate the unorganised markets.

3.1.3.2 Energy Retailers

The energy retailers buy energy from power producers and supply electricity services to demand customers. The services offered to the customers include low cost energy, predictable energy costs, power quality energy, and end-use energy savings. Some energy retailers also offer other utility services such as gas, telephone and TV cable.

3.1.4 Statutory Authorities

3.1.4.1 Electricity Regulator

The regulator is a statutory body that defines responsibilities and controls performance of the monopolies in the electricity industry. In general these monopolies are the transmission administrator, the transmission and distribution system operators, and the network owners.

3.1.4.2 Other Authorities

Local government authorities grant permits for building power lines and stations. Their objective is to protect landowners, communities and the environment from unrestricted development by the electricity industry and others. Environmental protection authorities control pollution from fossil fuel generation plants.

3.1.5 Summary of Stakeholder Roles in Deregulated Market

The tasks and responsibilities of the various market players are summarised in tabular form.

Key to the table:

- A: has authority to ensure that task is performed within standards or guidelines
- R: has responsibility for the task
- T: carries out the task
- I: provides key input into the process

Responsibility for some tasks can rest with one participant or another depending on the time frame being considered. Rather than duplicating the row, these tasks have multiple R and T entries, in this table.

Table 3.2 Tasks and responsibilities of the Various Market Participants

Tasks / Responsibilities	Regu-lator	T.A.	System Operator	Network Owner	Metering & Data Admin.	Power Producer	Demand Cust.	Market Operator	Energy Retailer
Develop Planning Criteria	A	R,T	I						
Plan Transmission Network Efficiently	A	R,T	I	I	I	I	I	I	I
Load Forecasting		T	T		I		I		I
Provide Access to Networks	A	R		T					
Ensure Building of new network assets		R	I	T		I	I	I	I
Operation and control of Transmission System			R,T	T	I				
System Reliability and Power Quality		R	R,T	I		I	I		
Emergency system operation			R,T	T					
Maintenance Planning (1week-5 years)		R,T	I	I		I			
Maintenance Scheduling (1weeks)			R,T	I		I			
Maintenance of network elements				T					
Manage Constraints and Minimise Congestion and Losses		R,T	R,T					I	
Dispatch of Ancillary Services		R	R,T			I			
Schedule Interconnector Flows			T					T	
Set network tariffs	A	R,T				I	I		I
Collect network charges		T			I				
Produce the Grid Code	A	R,T	I						
Network Protection		R,T	I	R,T					
Provide Trading Mechanisms			R					T	
Settle the market					I			T	
Ensure efficient network operation	R,A		T		I			T	
Ensure all market players enjoy equal admission rights	R,A	T							

3.1.6 Stakeholders Considered Further in this Report

This report deals with how the Transmission Administrator as network planner takes account of the new forces exerted by the stakeholders in the liberalised electricity market, which drive transmission development. Some of the stakeholders listed above can be omitted from further discussion, because they exert no driving force for development or because their objectives are better represented by other players.

Thus, the major stakeholders dealt with in the rest of this report are

- Demand Customer
- Power Producer
- System Operator
- Network Owner
- Regulator

3.2 NEW DRIVING FORCES

Liberalisation of the market for electricity has resulted in new, more complex forces, which drive development of transmission networks. The stakeholders, identified in the previous section, exert new and different driving forces, while the long-standing driving forces have reduced in importance.

3.2.1 Demand Customers

The principle aim of market liberalisation is to give customers greater choice through the introduction of competition in electricity production and supply. This gives demand customers new strengths, which they will exercise to achieve their objectives. The choices and new demands that customers make will have an impact not only on producers and suppliers, but also on the development requirements for transmission networks.

In cases where a surplus of generation / interconnection capacity exists, customer choice of supplier will determine the loading on generators, and hence flows on the network. Power flows through a network can also be impacted by contracts between supplier and customer from other interconnected systems. These flows, which are increasing as a result of liberalisation, put pressure on the network planner to increase transmission capacity and flexibility.

Unbundling of roles, as described in section 3.1, has led to transparency in transmission charges. Demand customers can now see the costs of connecting to and using the networks, and will attempt to have these costs minimised.

In many markets, because of a political requirement not to discriminate against remote regions, demand customers pay a uniform use of system (UoS) tariff, which is independent of distance. In other markets, locational signals exist but are not sufficient to compete with other factors of production. Thus, the impact of pricing on the spatial development of demand is negligible.

Demand customers may use on-site generation, load management and flexible working techniques to manage demand in response to time-varying energy and UoS tariff signals. A consequent reduction in peak demand may result in deferral of network reinforcements. (Flatter load profiles may also reduce the rating on network components because cyclical loading ratings may no longer be applicable.)

Customers are likely to require more choice in the security and quality of their supply. Tailored quality is not possible on a meshed system. However, the security level of local supply networks can be established depending upon the requirements of connected customers.

3.2.2 Power Producer

Liberalisation is opening up monopolies to competition in power production, which may lead to connection of new generators and puts pressure on old uneconomic units to close. These changes in connected generation capacity are likely to have a more significant impact on the network than unexpected load growth.

Changes in installed generation capacity can occur more quickly than the addition of network reinforcements. New combined cycle gas turbine type plant can generally be constructed within two or three years of decision; existing non-economic units may close in a much shorter period, depending on local grid rules. The changes in generation can lead to urgent reactive power requirements, and the need for increased network capacity into the area. Any delay in providing these can result in constraints on generators.

The new generators entering a competitive market will attempt to minimise their capital costs and maximise unit efficiency, typically at the expense of ancillary service capabilities. To ensure an adequate supply of these services, a minimum standard may be specified in code, or a market for these services may be created.

Small scale decentralised generation may reduce large-scale power station development. It will also reduce the net import of power into an area, and so may offset or postpone the need for development on the local supply network. On the other hand, because of the nature of renewable technologies, in particular wind generation, increased network reinforcements and/or a market for reactive power, spinning and non-spinning reserve may be needed to ensure network standards are maintained.

3.2.3 System Operator

The system operator will be under pressure ”to make the market work“ and will in turn seek maximum flexibility with minimum network downtime. As trading flows and opportunistic wheeling increase, the system operator will attempt to mitigate an increased level of network risk by seeking higher reliability and / or more redundancy relative to contracted flows.

In addition, the system operator will be forced by the regulator to reduce costs for managing the network and for ancillary services.

The system operators will seek to achieve their objectives through

- influencing planning and maintenance of the network to get a highly reliable and flexible network
- minimising losses

- achieving improvements in information and control, thus allowing greater utilisation of assets
- seeking provision of sufficient reactive power and other ancillary services
- applying pressure to remove transmission congestion

3.2.4 Network Owner

The principle objective of the network owner is to maximise shareholder value. Thus there will be greater emphasis on economics and less on technical excellence. The objective will be achieved in simple terms by reducing costs and/or increasing revenues.

Costs are generally more controllable than revenues or incomes. To reduce costs the owner may try to

- minimise operation and maintenance costs
- minimise the risk of investments
- dismantle redundant networks

Cautious investment, where the owner avoids risky network developments, works against the rapid response required by an open access market, as referred to above in section 3.2.2.

Transmission tariffs, which determine the owner's revenue, are generally regulated. The different methods of regulation can influence the owners' development priority.

For example, suppose a network owner is rewarded purely as a percentage of its regulatory asset base in any year; then if the long term reward exceeds the marginal cost of capital, there is an incentive for the owner to deliver the maximum asset base. In this case, owners will tend to argue for maximum open access flexibility in the optimisation equation.

If the owner were rewarded as a percentage of demand billed, then the asset owner would seek to minimise investment, in which case the owner would argue that future risks of asset stranding destroy a case for investment.

3.2.5 Regulator

One of the electricity regulator's key objectives is the protection of the network users from the monopolies within the industry, which it does through tariff regulation. Various methods of regulation exist, and these can influence network priorities, as illustrated in 3.2.4 above.

Other objectives include liberalisation of the electricity market, promotion of competition, and unbundling of market functions from monopoly organisations.

The electricity regulator therefore exerts the following forces on network development:

- minimisation of transmission prices
- minimisation of system operation costs
- ensuring sufficient capacity for open market, by offering incentives to build
- ensuring equity for all parties seeking network access
- ensuring long-term network reliability

The regulator has authority to back these forces, but in using its strength, it must be conscious of achieving a balance between the aims of the various stakeholders, in order for the market to work.

4 PLANNING FOR TRANSMISSION SYSTEM REQUIREMENTS

4.1 OVERVIEW OF THE MODELING PROCESS

A model is proposed here which is based upon a range of views of the future and a range of perspectives on development priority. Since development priorities and interactions involved in decision-making are between real persons and interest groups, whose logical action can be tempered by emotional reactions, it is impossible to predict with certainty that a solution will satisfy all stakeholders. It is intended here that a pseudo-optimisation is created aimed at avoiding wasteful effort by selecting a bundle of projects that maintain a reasonable stakeholder balance. The rationale and justification for this approach, is that:

- best practice managers do this instinctively
- failure to maintain a position within a safety zone for all stakeholders causes disproportionate rectification expenditure

The following process is suggested as forming the basis for the analysis.

- Each significant view of the future is represented by an internally consistent scenario, see Table 4.1.

- For each scenario, network analysis is carried out to determine the development options, their expected project life and effect on other projects.

- From focus groups or otherwise the major stakeholders perception of the importance of the impact axes is determined as a generic table which can be applied to all projects, see Table 4.2.

- A judgement is made on the relative importance of stakeholders in the decision-making process, see Table 4.3.

- Using multiplication by factors representing the stakeholder importance, a table of relative importance of the impact axes is produced, see Table 4.4.

- Each scenario and therefore each project is then placed into a matrix table and its effect on each major impact axis (network cost, environment etc.) is quantified, see Table 4.5 and 4.6.

- Projects with the highest overall score are likely to offer overall benefits to the stakeholder group.

- Since this analysis has been done for each scenario, a technique is used to select the best projects across all scenarios.

- Projects are examined to determine their requirement to fulfil planning standards across the range of scenarios and defined as "Must do", "Speculative" or "Hedging" actions.

- The results are sanity checked, to ensure that the "Must do" and "Hedging" projects are included in the list of preferred projects. This is important since these developments are required to maintain standards.

4.2 SCENARIO MODELLING

Competition and customer choice has the effect of increasing the uncertainty that a planner must deal with in forecasting generation production, customer demand, and interconnector flows. In addition, role unbundling within the electricity industry has created new stakeholders, each with their own objectives for network development. These stakeholders have varying strengths with which to pursue their objectives.

In this new dynamic environment, the planner needs to consider more flexible approaches to modelling and developing the network, if uncertainty and risk management are to be accounted for while satisfying stakeholder expectations. Scenario modelling is a way of taking account of a number of views of the future [3].

New Factors in Scenario Modelling
In open-market systems non-load based scenarios could be required to take account of the following conditions, inter alia:

- The transmission asset owner may see opportunities to increase revenue by increased transport to non-native customers
- Changing technologies, factor prices or factor conditions may encourage the development of new sources of generation
- The power station development time and the notice that a generator can give before shutting down can be very short
- Tariffs may not be fully controllable and may not be sending transmission efficient signals
- The balance of embedded generation and centrally dispatched generation may be changing
- External generation may be becoming more economically efficient leading to large inward power transfers
- More customers may be contracting directly with independent power producers, who will want to manage their risk by being able to deliver energy up to their commitment

The planner will need more vision and new tools to help create these scenarios. If a large number of scenarios exist it is expedient to classify them and so identify the most relevant.

Scenarios Construction and Analysis
Scenario construction and ranking tools are often based on performing an extended number of simulations and generating a database of results. Some formalised methods are listed below:

- Decision trees
- Neural networks
- Principal component analysis

In these methods, the potential impact of scenario factors is being assessed against their probability of occurrence. At least one organisation assesses the probability of each generating set remaining in operation for a further year and constructs scenarios accordingly. The same principle is applicable to all scenario elements. This is likely to give rise to a matrix as follows:

Table 4.1 Scenario – Probability Table

Scenarios	Description	Probability
A1	Changes from present in A1	15%
A2	Changes from present in A2	25%
B1	Changes from present in B1	60%

The network performance of the existing system can be established for each scenario and a list of developments prepared.

4.3 EVALUATING THE ALTERNATIVES TAKING INTO ACCOUNT THE STAKEHOLDERS' DESIRES

Optimisation Philosophy
The proposed way to rank projects under each scenario is to consider stakeholder interests, both in the short and longer term. In times of increasing uncertainty, decision-makers tend to consider only the immediate effects and decisions are often taken to hedge uncertainty rather than plan for the longer term. Typically, where Regulation spans a defined period, this is the horizon that will guide decision-making.

The diverse drivers mean that there is no unique stable optimisation of the bundle of transmission projects, which should be advanced at any time or within any time span. Put another way, each stakeholder group will have a different view on what should be done. The task of the decision-maker is to make the best judgement of the way forward.

Leaving aside analytical rigour, good decision-making balances the group of projects to maintain satisfaction on the part of all important stakeholders. Senior executives in all industries recognise that each stakeholder has a comfort zone and a no-go area. The boundary is not always well defined and there may be a dynamic associated with it. Boundaries exhibit some of the properties of osmotic membranes, in that the organisation may initially hardly realise that it has crossed a stakeholder chaos boundary, but once crossed, the environment is entirely changed, and returning to the old environment requires enormous energy or is impossible. Organisations need to understand where the stakeholder boundaries are and study the boundary dynamics if they are to avoid interfacing with or crossing into no-go areas. In this way they save much unnecessary recovery work.

The problem could be converted to a precise multi-variant optimisation within the time domain, except for externalities that may have unpredictable or disproportionate effects on the confidence and expectation level of the stakeholder groups. It is therefore suggested that these human factors prevent true mathematical optimisation. The best that can be done is to represent each stakeholder as a quantitative axis in a multi-dimensional analysis and select a bundle of projects that lies on the safe side of the multi-dimensional chaos boundary surface. Any combination of projects that maintains the organisation sufficiently far from the chaos surface would then form a reasonable non-wasteful decision set, which nonetheless has a margin of safety from chaos.

Project - Stakeholder Analysis
The following approach is seeking this pseudo or softer optimisation of projects.
Stakeholder desires can be expressed as in the following matrix:

Table 4.2 Stakeholder / Criteria Matrix

Stakeholder desires (per unit rating *						
Stakeholders	Network Reward	Customer Satisfaction			Environ-mental impact	Total
		Network Charge	Flexibility	Quality		
Power Producers						1
Demand Customers						1
System Operator						1
Network Owner						1
Regulator						1

** In the per unit system each entry is a decimal number and each row must add to 1.0.*

At any point in time decision-makers evaluate the relative importance of stakeholders in arriving at a view. The issues affecting stakeholder importance may be short term or structural. Decision-makers need to assess how far they are from a chaos boundary with stakeholders, at what rate they are approaching the boundary and the consequences of meeting it. This will lead to a set of stakeholder weightings. Dynamic issues are relevant in arriving at these weightings if the result is to avoid exciting wasteful oscillatory behaviour. On questioning, managers are likely to be able to identify the present weighting which they would give stakeholders and the maximum and minimum weighting limits for each stakeholder (mathematical boundary conditions).

Table 4.3 Goal / Stakeholder Matrix

Stakeholders	Power Producers	Demand Customers	System Operator	Network Owner	Regulator
Present [1] Max [2] Min [2]					

1) *per unit rating where the row should total to 1.0.*
2) *these values will not total to 1.0 since they represent managers views across a range of extreme scenarios.*

By multiplying the Matrix 4.2 by the **present** row in 4.3, the stakeholders are eliminated showing the importance of impact axis or criteria on the goal.

Table 4.4 Goal / Criteria Matrix

Criteria	Network Reward	Network Charge	Flexibility	Quality	Environmental Impact
Goal					

The above method has the advantage that stakeholders are questioned only once. Should a new alternative be proposed, it will only be necessary to evaluate its effect on the criteria, without having to present it to the stakeholders.

The important issue here is that this analysis is for a point in time. As the political, business, social and environmental climates change, stakeholder importance will vary within the maximum and minimum parameters stated in Table 4.3 above. Decision-makers may therefore wish to assess the effects of global scenarios on their investments by constructing a number of Goal/Criteria matrices based upon different stakeholder weights.

For each scenario an alternatives / criteria table can be constructed as follows:

Table 4.5 Alternatives / Criteria Matrix

Impact of Projects on Key Metrics (desires)					
Projects	Network Reward	Customer Satisfaction			Environmental Impact
		Network Charge	Flexibility	Quality	
Alternative 1					
Alternative 2					
Alternative 3					

It is difficult to find measures that are compatible across a range of different variables. It is suggested that a scale (say -5 to 0 to +5) be used instead of money. A project which increases network charge by a very small amount might be valued at -0.5 or -1; since it is neutral on network profitability it scores 0 in network rewards, but it greatly improves flexibility by removing a transmission constraint so scores +2.5 in that column. It maintains local voltage and removes harmonics so it scores well on quality. It is a SVC on an existing site and thus has minimum environmental impact i.e. 0.

Table 4.5 is repeated for each scenario that has been deemed important in the preliminary work.

The criteria may now be eliminated multiplying each of the matrices developed in Table 4.5 by single row Goal /Criteria Matrix (Table 4.4). In this way, Alternative 1 has a single "goodness" value for the Scenario 1 and a different "goodness" value for scenario 2 etc.
Taking 6 scenarios a matrix emerges as shown.

Table 4.6 Performance of each Alternative under each Scenario

Scenarios Alternatives	S1	S2	S3	S4	S5	S6
Alternative 1	+ or -	+ or -	+ or -	+ or -	+ or -	+ or -
Alternative 2	+ or -	+ or -	+ or -	+ or -	+ or -	+ or -
Alternative 3	+ or -	+ or -	+ or -	+ or -	+ or -	+ or -

Some developments will be required for all scenarios and are therefore unambiguously required. Others are less obvious. Following such an analysis, developments can be categorized as follows:

Must do

Speculative investment

Hedging manoeuvre

Must do - This is a clearly needed change in nodal transfer capacity to meet the security standards and applies across the range of credible scenarios. The change may be required for thermal, voltage, short circuit level or stability requirements.

Speculative investment - Here the transmission network provider holds a strong view that a scenario or subset of scenarios will dominate the future and that the risks are worth the prospective returns. Each type of investment has a risk/reward profile. In theory, the decision-makers should not take risks in aggregate beyond the risk profile expected by owners of this type of investment. The decision to carry out such an investment may require a review of the "must do" and hedging investments since the required nodal capacities may be altered.

Hedging investment - The scenarios may require very different reinforcements and there may be no clear signal as to their relative credibility. The transmission administrator may be unwilling to invest and risk a stranded asset. In this case it is likely that tactics will be applied to hedge the risk of not investing. Typical arrangements are re-locatable devices, mobile generating plant, advanced control, FACTS devices and improvement in maintenance methods. Where standards are phrased to accept risk assessment rather than purely deterministic techniques, these methods, taken together, can be used to defer additional installed nodal transfer capacity until the scenarios become more certain.

4.4 FINAL DECISION-MAKING

Having identified the optimal solution under each scenario from Table 4.6, the final step is to choose the optimal solution to cope with the different possible scenarios [4].

Methods that have been applied in the past to arrive at the best overall solution are:

- Settling on a most likely or “reference scenario” and allowing adequate margins to offset possible uncertainties. This is a deterministic solution, based on a single criterion (in general minimisation of costs).

- In more sophisticated cases, uncertainties have been explicitly taken into account, with known probability laws, and the planning criterion e.g. the minimisation of the expected value of costs on multiple scenarios (Monte Carlo methods). The use of mean costs as a decision criterion is adequate for these phenomena, which can be considered as "high frequency perturbations" of an otherwise relatively certain future, because a representative sample of all values is expected to occur along the planning period[2].

In the open market environment uncertainty is too high to have confidence in a reference scenario.

A straightforward approach to dealing with the uncertainty would be to multiply the performance of each solution under each scenario by the associated probability of occurrence, as listed in column 3 of Table 4.1.

The projects can then be arranged in order, beginning at the highest benefit. At this point the list can be checked to ensure that the "must do" and hedging projects are above a cut-off band established by availability of resources. It is recognised that, in the new environment, hedging against uncertainty has an important place in transmission planning.

Where "must do" projects are below the cut-off, this is because the cost of maintaining regulatory standards gives less total benefit to all stakeholders than other work. Regulatory authorities will be obliged to consider either the level of resources afforded or the appropriateness of the standard.

The probability of scenarios is not the only approach to evaluating the expected value from projects. This *expected value* approach, which assumes that the best plan is the one that maximises the expected performance of network reinforcements over the different scenarios, can distort the result. Some uncertainties resulting from open access are "low frequency phenomena". This would be the case if one of the scenarios predominates over the entire planning period. The meaningfulness of investment decisions, which are optimal on the average for all scenarios, is then questionable.

Other decision criteria have been introduced, which recognise that hedging against risk can be a better approach.

The *Risk Analysis*, or *vulnerability*, *paradigm* indicates a preferred solution as one that minimises the regret felt ex-post by a decision manager, after verifying that the decisions he had made were not optimal, given the future that in fact has occurred [5]; in other words, this method indicates that the best choice is the one that limits damage when the worst scenario occurs.

A detailed description of these and other assessment methods is contained in another CIGRE Report [6]. The uncertainty concepts described in that Report for single objective problems need to be extended to the multi-objective problems described here.

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[2] One typical example is the operation of a thermal generation system: during 10 years of operation, one expects that the most likely combinations of generation outages will occur.

4.5 POPULATING THE MODEL WITH DATA

Data characteristics within the model
In this model the relation between the stakeholders and the network criteria is fixed for all projects, i.e. the stakeholders-criteria table has constant values. This is an assumption that might be discussed, and more sophisticated models might use utility functions to model the stakeholder attitude towards the criteria.

Stakeholder / Criteria Matrix (Ref. Table 4.2):
Focus groups and stakeholder sampling can be used to populate the model. There are a number of ways to weight the relation between a stakeholder and his desires. The following are examples:

- Pairwise comparison
- Importance ranking
- Ranking by citation
- Distribution of points
- Score scale

There is no best method. Factors in the choice of method are the sample size available and the time available for research. It is important to achieve a fair allocation of stakeholder desires since the final out-turn of the model may differ significantly with a small change of weights. It is therefore recommended that modellers:

1. verify the weights by at least two independent methods;
2. check the sensitivity of the results of the model to small changes in the weighting of desires.

Goal / Stakeholder Matrix (Ref. Table 4.3):
This table is subjective. Regulatory authorities will have a strong view on the importance attributed to the different stakeholders. It is also essential to understand the importance of historical and current situations when constructing this table. While generic guidance will be difficult, it is possible to borrow from medical science, where a range in each parameter is published for a healthy body. Outside this range indicates pathological issues. It is then necessary to isolate acute problems for which the parameter is temporarily elevated or depressed, from a chronic situation, which will continue to worsen. If the entire analysis is to be acceptable to all stakeholders, it will be important to first gain agreement on the normal ranges of stakeholder weightings. It then follows that decision-making and regulation will focus on the scope for movement within these bands.

Goal / Criteria matrix (Ref. Table 4.4):
This is a calculated table, which requires no new source data.

Alternatives / Criteria Matrix (Ref. Table 4.5):
This is known in decision analysis as impact table. It shows the effect of alternatives (projects) on the set of impact factors or stakeholder desires. There is a tendency to attempt to

reduce the measure to a financial value, as economists do with environmental burden. It is preferable to use interval variables. This avoids the issue of placing a monetary value on environment, quality and flexibility, which seems fruitless if the value is to be multiplied by a set of weighting figures.

Other Tables:
The remaining tables are calculated and require no new data

Note
It is important to consider whether one project has an effect on others. Ranked triangulated matrix approaches are available to deal with this complication [7].

A further influence on the ranking is caused by the mutual relation between the stakeholders. Detailed modelling of these relations would require a mix of multi-actor analysis and game theory.

4.6 TOOLS/MODELS

When the number of alternatives and or scenarios becomes too large, the lookup tables used for the small examples developed in this report would have become too cumbersome and specific software tools would be required. Some commercial-grade packages are available for multi-criteria optimisation and decision-making under uncertainty. These were developed for marketing studies or localisation of large infrastructure e.g. railway lines or harbours. They are usually based on spreadsheets and have an intuitive interface, which facilitates learning and hides the mathematical part of the methods. Some theoretical models have also been implemented by Universities or research centres for specific use in electric utilities.

For scenario identification, little commercial software exists. Some utilities have developed proprietary software, to perform probabilistic analyses of various variables e.g. power plant opening and closure, demand growth, embedded generation growth, export patterns [8, 9]. This is relatively easy for an "electrical" simulations, as the building blocks of such software are well proven tools e.g. OPF, but interpretation of results requires additional expertise in advanced statistical methods.

5 AN EXAMPLE

This chapter provides an example of the planning methodology described in Chapter 4, using a simple three-bus test system, as shown in Fig. 5.1.
Suppose the planning horizon consists of one period only: the system is analysed in its present configuration and in a snapshot of how it will be in 5 years' time. At present, the existing load at bus C is served mainly by the existing generator at bus A, but there is a fair probability that:

- a new generator (NG) will connect to bus B;
- there will be a major load increase at bus C;
- generating capacity at bus A will decrease due to cheaper imports from the interconnector.

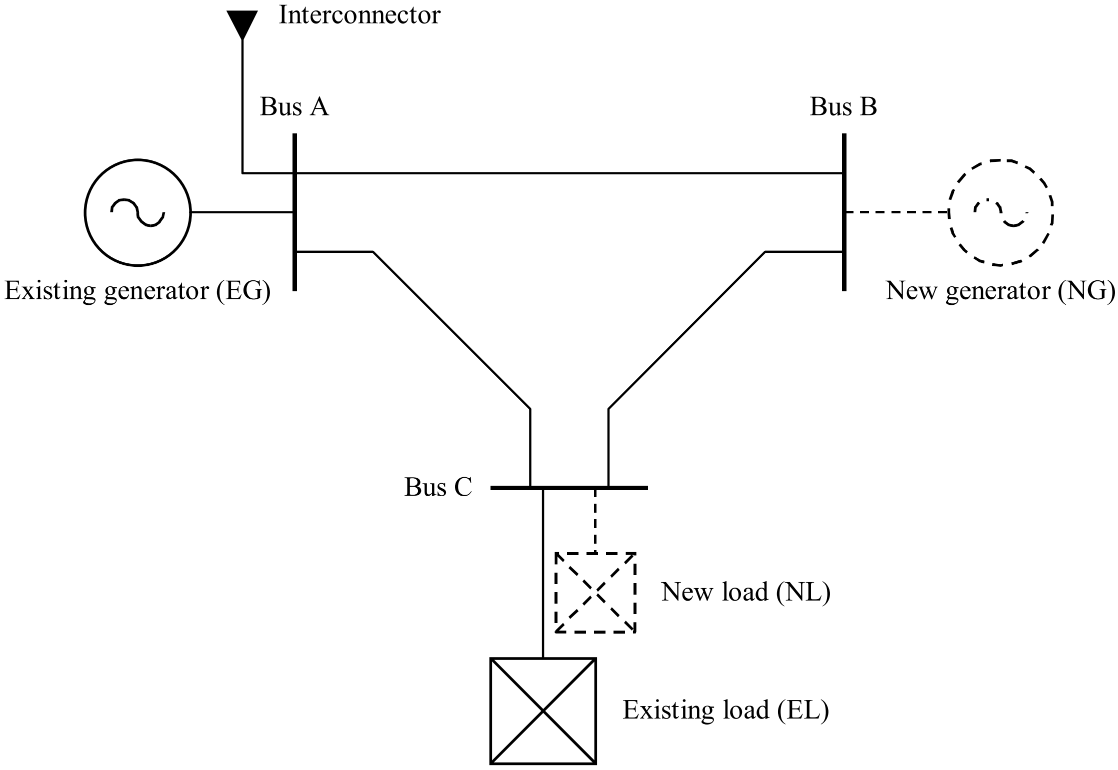

Figure 5.1 Three-bus test system

According to system experts, the most likely scenarios and the associated probabilities of occurrence are those presented in Table 5.1.

Table 5.1 Likely scenarios and probabilities of occurrence

Scenario name	Existing generator	New generator	New load	Probability
S1	Unchanged	Doesn't connect	Doesn't connect	0.12
S2	Unchanged	Doesn't connect	Connects	0.30
S3	Unchanged	Connects	Connects	0.18
S4	Reduced capacity	Doesn't connect	Doesn't connect	0.08
S5	Reduced capacity	Doesn't connect	Connects	0.20
S6	Reduced capacity	Connects	Connects	0.12

System performance under the different scenarios can be briefly stated as follows:

S1: the system complies with planning standards but works close to its limits;

S2: the critical contingency is the loss of line AC, which results in thermal overload of line AB and excessive voltage drop at bus C;

S3: the system complies with planning standards (simultaneous outage of line AC and of the new generator is not taken into account);

S4: the critical contingency is the loss of line AC, which results in excessive voltage drop at bus C;

S5: the critical contingency is the loss of line AC, which results in thermal overload of line AB and excessive voltage drop at bus C (greater than in scenario S2);

S6: the system complies with planning standards.

Five alternatives have been identified to reinforce the network (in order of increasing cost):
A1: no action;
A2: negotiating a load-reduction contract at bus C (that is to say, the load at bus C accepts to be curtailed if and when the critical contingency happens, and receives a fixed annual premium in exchange for that);
A3: reconductoring line AB;
A4: installing an SVC at bus C;
A5: doubling line AC.

Timescales
Due to construction, authorisation or negotiating lead-time, a decision has to be taken in the first period, and the performance of the system in the second period will depend on the past decision and the scenario, which will actually turn out to be true.

Other Assumptions
The alternatives can be evaluated according to five criteria:
- Network reward: an index of the performance based upon additional reward to the network owner.
- Network charge: network charges are almost entirely borne by demand customers, in the form of a per kW or a per kWh fee; therefore, new investments not accompanied by an increase in load will lead to an increase of network charges.
- Flexibility: this criterion expresses the ability for the system operator to perform its task with reasonable ease and without taking excessive risks.
- Quality: this criterion expresses the ability of the network to deliver power within license standards and without interruptions.
- Environmental impact: this criterion measures the degradation of the natural environment caused by new transmission facilities.

5.1 TAKING INTO ACCOUNT THE STAKEHOLDERS' DESIRES

Five major stakeholders have been identified in Chapter 3:
- Power Producers (the plants at bus A and B are supposed to be owned by the same company);
- Demand Customers;
- System Operator;
- Network Owner;
- Regulator.

By applying one of the methods described in paragraph 4.5, the importance that each stakeholder attaches to each criterion can be identified. An example of this is shown in Table 5.2.

Table 5.2 Stakeholder / Criteria matrix

Criteria Stakeholders	Network Reward	Network Charge	Flexibility	Quality	Environ. Impact
Power Producers	0.6	0.2	0.1	0.1	0.0
Demand Customers	0.0	0.6	0.0	0.4	0.0
System Operator	0.0	0.0	0.7	0.3	0.0
Network Owner	0.6	0.0	0.1	0.0	0.3
Regulator	0.0	0.1	0.0	0.0	0.9

Likewise, by applying one of the methods described in paragraph 4.5, the planner can express the relative importance of each stakeholder. The assumed weighting is shown in Table 5.3.

Table 5.3 Goal / Stakeholder matrix

Stakeholders	Power Producers	Demand Customer	System Operator	Network Owner	Regulator
Goal	0.1	0.4	0.1	0.2	0.2

By multiplying these two matrixes, we can eliminate the stakeholders and identify the relative importance of each criterion with respect to the final goal; the results are shown in Table 5.4.

Table 5.4 Goal / Criteria matrix

Criteria	Network Reward	Network Charge	Flexibility	Quality	Environmental impact
Goal	0.18	0.28	0.1	0.2	0.24

5.2 EVALUATING THE ALTERNATIVES IN THIS EXAMPLE

Each alternative has different merits under each scenario.

The performance of each alternative with respect to each criterion will be expressed on a –5 to +5 qualitative scale, -5 meaning a very poor performance, +5 a very good performance and 0 no change.

Assumptions in this Example

- Network reward increases slightly when new facilities are built.
- As network charges are allocated to demand customers, these charges will increase when new facilities are built and little or no new load is connected, and will decrease if nothing is built and new load is connected. Moreover, the load-reduction contract has no impact on access charges because demand customers receive the premium, but have to pay higher access charges to compensate for this.
- Flexibility and reliability indexes will be negative if a load curtailment is necessary; they will be slightly worse if the load curtailment has to be preceded by a warning (in the case of the contract), because this causes additional difficulties to system operators compared to sudden and unexpected load shedding. Flexibility and reliability indexes will be positive if the SVC is installed or line AC is doubled because of an overall increase in reliability and easier maintenance.

- Quality deteriorates very badly if a large load reduction is needed (for both thermal and voltage reasons), badly if a lesser load reduction is needed (for voltage reasons or thermal reasons only); in both cases, the performance deterioration is considered to be slightly less important if the reduction is contracted beforehand.
- Environmental impact[3] will be considerable for overhead power lines (and, to a lesser extent, also for other electrical equipment such as the SVC because of alleged electro-magnetic compatibility issues).

As far as the reinforcements are concerned, we will assume that:

- The amount of load to be shed if no action is taken or if the contract is signed will depend on the scenario: for example, a large load reduction is needed for both thermal and voltage reasons in scenario S5, a medium load reduction is needed for both thermal and voltage reasons in scenario S2 and a small load reduction is needed for voltage reasons only in scenario S4.
- Reconductoring line AB will solve thermal limitation problems but not voltage drop problems: load shedding will thus remain necessary under some scenarios.
- The SVC will solve all voltage problems and also provide some relief to thermal problems, because of a better power factor on line AB.
- Doubling line AC will always solve all the problems.

The performance of each alternative under scenario S1 is presented in Table 5.5.

Table 5.5 Alternatives / Criteria matrix under scenario S1

Criteria Alternatives	Network Reward	Network Charge	Flexibility	Quality	Env. Impact
No action	0	0	0	0	0
Load-reduction contract	0	0	0	0	0
Reconductoring line AB	1	-2	0	0	-1
SVC at bus C	2	-3	2	0	-1
Doubling line AC	3	-5	5	0	-5

Since this scenario corresponds to a situation in which there is no major evolution in the system, the technical performances are unchanged and there is an increase in network charges if new facilities are built.

The performances of each alternative under scenario S2 are presented in Table 5.6.

[3] Notice that the environmental impact merit is the same under each scenario and that it is never positive (as no overhead lines are ever decommissioned).

Table 5.6 Alternatives / Criteria matrix under scenario S2

Criteria Alternatives	Network Reward	Network Charge	Flexibility	Quality	Env. Impact
No action	0	2	-2	-3	0
Load-reduction contract	0	2	-3	-2	0
Reconductoring line AB	1	0	-2	-1	-1
SVC at bus C	2	-1	2	0	-1
Doubling line AC	3	-4	5	0	-5

As this scenario entails a large increase in load, if no action is taken a medium-sized load shedding is necessary when the critical contingency happens, and a smaller but still significant part of load has to be shed if only the thermal problem is solved (by reconductoring line AB). If the SVC is installed or if line AC is doubled, no load shedding is necessary; however, there will be a slight increase in network charges that can be explained by threshold effects, since the capacity of such equipment is larger than what is strictly needed to accommodate the additional load.

The performances of each alternative under scenario S3 are presented in Table 5.7.

Table 5.7 Alternatives / Criteria matrix under scenario S3

Criteria Alternatives	Network Reward	Network Charge	Flexibility	Quality	Env. Impact
No action	0	2	0	0	0
Load-reduction contract	0	2	0	0	0
Reconductoring line AB	1	0	0	0	-1
SVC at bus C	2	-1	2	0	-1
Doubling line AC	3	-4	5	0	-5

Since under this scenario the thermal and voltage problems caused by the new load are eliminated by the presence of the new generator, the technical performances of the different alternatives are the same as under scenario S1; on the other hand, the impact on network charges will be the same as under scenario S2.

The performances of each alternative under scenario S4 are presented in Table 5.8.

Table 5.8 Alternatives / Criteria matrix under scenario S4

Criteria Alternatives	Network Reward	Network Charge	Flexibility	Quality	Env. Impact
No action	0	0	-2	-1	0
Load-reduction contract	0	0	-3	0	0
Reconductoring line AB	1	-2	-2	-1	-1
SVC at bus C	2	-3	2	0	-1
Doubling line AC	3	-5	5	0	-5

This scenario is similar to scenario S1; however, a small-sized load shedding is needed if no action is taken as, due to the reduced voltage support provided by the existing generator, voltage problems arise even if no new load connects to the system.

The performances of each alternative under scenario S5 are presented in Table 5.9.

Table 5.9 Alternatives / Criteria matrix under scenario S5

Criteria Alternatives	Network Reward	Network Charge	Flexibility	Quality	Env. Impact
No action	0	2	-2	-5	0
Load-reduction contract	0	2	-3	-4	0
Reconductoring line AB	1	0	-2	-5	-1
SVC at bus C	2	-1	2	0	-1
Doubling line AC	3	-4	5	0	-5

The performances of the different alternatives under this scenario are almost the same as under scenario S2; the only difference being that in this case if no measure is taken to relieve the weakness of the system voltage (i.e. when the SVC or the double line are not installed), a large amount of load must be shed.

The performances of each alternative under scenario S6 are presented in Table 5.10.

Table 5.10 Alternatives / Criteria matrix under scenario S6

Criteria Alternatives	Network Reward	Network Charge	Flexibility	Quality	Env. Impact
No action	0	2	0	0	0
Load-reduction contract	0	2	0	0	0
Reconductoring line AB	1	0	0	0	-1
SVC at bus C	2	-1	2	0	-1
Doubling line AC	3	-4	5	0	-5

Under this scenario the thermal and voltage problems caused by the new load are eliminated by the presence of the new generator. The performances of the different alternatives are the same as under scenario S3.

5.3 CHOOSING THE FINAL SOLUTION

By weighting the performance of each alternative according to each criterion using the weights of Table 5.4, the performance of each alternative under each scenario can be obtained from Table 5.11.

Table 5.11 Performance of each alternative under each scenario

Scenarios / Alternatives	S1	S2	S3	S4	S5	S6
No action	0.00	-0.24	0.56	-0.40	-0.64	0.56
Load-reduction contract	0.00	-0.14	0.56	-0.30	-0.54	0.56
Reconductoring line AB	-0.62	-0.46	-0.06	-1.02	-1.26	-0.06
SVC at bus C	-0.52	0.04	0.04	-0.52	0.04	0.04
Doubling line AC	-1.56	-1.28	-1.28	-1.56	-1.28	-1.28

Finally, by weighting each scenario by its probability of occurrence, the overall performance of each alternative can be evaluated and the "best solution" can be identified as presented in Table 5.12.

Table 5.12 Overall performance of each alternative

Alternatives	Overall performance
No action	-0.064
Load-reduction contract	-0.006
Reconductoring line AB	-0.564
SVC at bus C	-0.072
Doubling line AC	-1.336

This analysis indicates that the load-reduction contract is the best solution:

- it is low cost and environment-friendly
- it performs reasonably well under the majority of scenarios.

However, if a mini-max regret approach had been adopted as presented in Table 5.13, the entries for which can easily be obtained from Table 5.11, the best solution would have been to install the SVC. This is probably due to the fact that installing the SVC would turn out to be the best option if the worst case, scenario S5, happens. As scenario S5 has a relatively low probability of occurrence, the balance does not tilt in favour of installing the SVC, an expensive option, when a probability-weighted choice is made. When a regret-based choice is made, on the contrary, all scenarios are considered to have the same probability of occurrence. This leads to selecting the alternative that offers the best hedge, even against an unlikely scenario.

Table 5.13 Maximum regret associated to each alternative

Alternatives	Max regret
No action	0.68
Load-reduction contract	0.58
Reconductoring line AB	1.30
SVC at bus C	0.52
Doubling line AC	1.84

6 CONCLUSION ON "NEW" OPTIMISATION METHODS

Many of these methods are not used in transmission planning yet, and few software packages adopt them; nonetheless their concepts seem to align with both social and business objectives and are thus becoming more familiar.

While the methods described do not claim to provide a unique “best” solution by rigorous mathematical modelling, multi-criteria optimisation and decision under uncertainty methods have undeniable advantages:

- they constitute a method to collect and classify hard and soft information;
- they create a better understanding of how the problems and solutions are perceived by the different stakeholders;
- they constitute a method to incorporate these different judgements in an analytical framework;
- they provide an alternative to the simple economical valuation of the criteria;
- they impose a structure on research and studies required for the decision-making process and hence avoid a haphazard approach to wider accountability;
- they build consensus.

Some disadvantages are recognised:

- using multi-criteria methods could put pressure on stakeholders to reveal preferences or intentions which they prefer not to disclose;
- some methods are rather complex for assimilation by non-experts;
- if multi-criteria or decision under uncertainty evaluation is presented in an obscure way, it can be perceived as a scientific way to disguise a decision already taken.

It follows that to gain acceptance, careful consideration will need to be given to how to explain pseudo-optimisation methods and tools to a range of stakeholders. Stakeholder and decision-maker involvement in the development of methods and tools is likely to build confidence that the process is honest. Audit of the validity of inputs will serve to improve confidence that the tools are used in a fair and non-discriminatory way.

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APPENDIX: DECISION METHODS TAKING INTO ACCOUNT THE STAKEHOLDERS' EXPECTATIONS

Once the stakeholders' expectations and driving forces are taken into account, the process of network optimisation becomes one of « multi-criteria optimisation ».
In a mathematical formulation, the goal is to find the alternative that maximises the utility for each stakeholder:

$$\max u(x) = \begin{bmatrix} u_{s1}(x) \\ u_{s2}(x) \\ \vdots \\ u_{sn}(x) \end{bmatrix} \tag{A.1}$$

with $x \in X$, the set of feasible alternatives[4] (including the option of not doing anything…), and $u_{si}(x)$ is the utility for stakeholder i of alternative x (of course $u_{si}(x)$ can be further decomposed in sub-utilities).
The solution of this problem, which bundles mathematical and psychological concepts (the "theory of decision"), can be obtained in three steps:

1. transforming the shareholders' desires into a homogeneous set of objectives;
2. eliminating the dominated (or "non paretian") solutions;
3. taking the final decision.

Step 1 consists in taking the shareholder's desires, which are often expressed in different scales, both qualitative (strongly opposed, favourable) and quantitative (this projects represents an expense of €200.000 for me), and converting them into numerical values, all with the same scale.

Step 2 states that a rational decision-maker should never choose a dominated alternative; an alternative y is said to be dominated by an alternative x if, for each stakeholder, the utility of y is less than that of x: $u_{si}(y) \le u_{si}(x)$ for each i.

For example, if we have two options and two stakeholders, whose preferences are structured as follows:

	Stakeholder 1: System Operator Criterion: voltage drop	Stakeholder 2: Environmentalists Criterion: Environmental Impact
Alternative x	10%	5
Alternative y	12%	10

as the criteria have to be minimised, alternative x clearly dominates alternative y.

[4] We suppose that the number of alternatives is sufficiently small so that it is possible to explicitly describe each of them. If this is not the case, mathematical models and computer tools have to be utilised to discard dominated alternatives and select one project in the set of Pareto-optimal solutions.

Step 3 is the most complex one, and many theoretical methods are available to perform it, some of which have been tested on real-life problems.

Some of the best-known methods are:

- The classical method, in which a weight is associated to each criterion (stakeholder), thus transforming the multicriteria problem into a monodimensional one.
- The hierarchical analysis (Saaty method), which tries to make weight selection more objective by decomposing the problem in many subparts, comparing each possible couple and then recomposing the problem.
- The TOPSIS method, which tries to identify the alternative closest to an ideal "optimal" one.
- The ELECTRE methods, which try to identify relationships between alternatives based on a relaxation of the dominance concept.

In the following paragraphs, we will give a short description of each of these methods, which constitute quite a new field of Operations Research.

The classical method
The easiest way to solve a multi-criteria optimisation problem involves applying a weight to each stakeholder, thus reducing the multi-objective optimisation to a single-objective, very easy problem:

$$\max u(x) = w_{s1} \cdot u_{s1}(x) + w_{s2} \cdot u_{s2}(x) + \ldots + w_{sn} \cdot u_{sn}(x) \quad \text{(A.2)}$$

There are several methods to obtain the weights:

- Substitution rate: the decision-maker is asked by how much criterion c_i should be increased to compensate a decrease of criterion c_j of one unit; by repeating the process, a vector of weights can be obtained.
- Allocation method: this method consists in asking the decision-maker to allocate 100 points among the criteria in order to show their relative importance to him.
- Importance ranking: this method consists in asking the decision-maker to rank the criteria by importance; an arbitrary weighting function is then applied in order to obtain numerical values.

All these methods are not very satisfactory because of the great subjectivity involved in attributing the weights.

A more robust method is pairwise comparison, which will be described in the following paragraph.

The AHP method
Professor Saaty of the Wharton Business School developed the AHP (Analytical Hierarchy Process) as a method to introduce some objectivity in determining the weights.

The AHP method is used to decompose the hierarchy of criteria and determine the associated weights.

The decomposition of each criterion into sub-criteria (which could be called for example, stakeholders and attributes), with the main goal at the beginning and the alternatives at the end, is obtained as shown in Fig. A.1 and allows a fuller representation of all the facets of the problem than that of the classical method.

The weight associated to each intermediate objective is assumed to represent its relative importance in the attainment of the main goal. AHP is then useful both for identifying the weights for later use with another method and for aggregating the intermediate performances in order to obtain the global ranking of the alternatives.

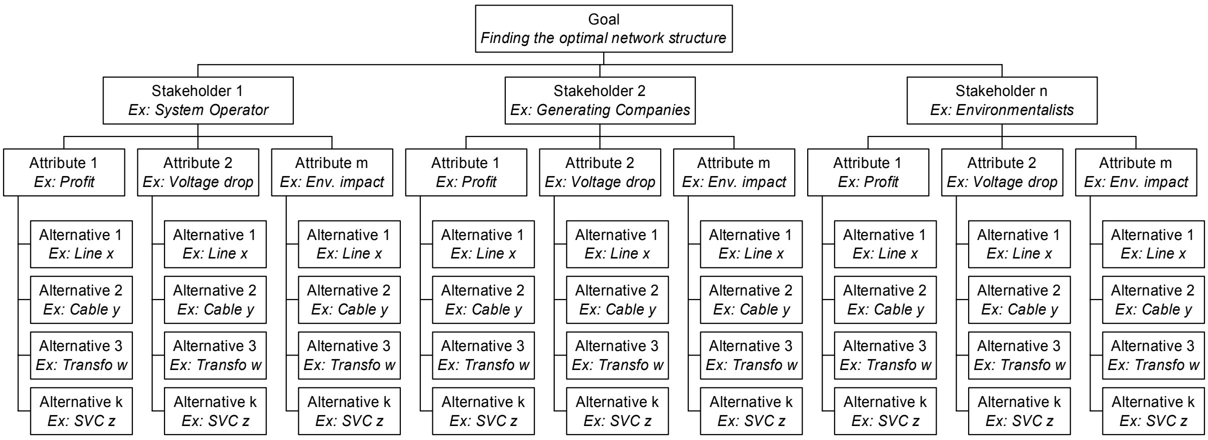


Figure A.1 Example of an AHP tree

As far as the determination of weights is concerned, the basic point of this method consists in replacing the overall comparison of criteria with pairwise comparisons between couples of criteria of the same level.

For this comparison, the following scale[5] must be used:

- if the attributes c_i and c_j have an equal importance, their ratio will be $a_{ij} = 1$;
- if c_i is slightly more important than c_j, then $a_{ij} = 3$;
- if c_i is strongly more important than c_j, then $a_{ij} = 5$;
- if c_i is very strongly more important than c_j, then $a_{ij} = 7$;
- if c_i is extremely more important than c_j, then $a_{ij} = 9$;
- $a_{ij} = 2,4,6,8$ is used for intermediate situations.

A matrix of comparisons between all the criteria of the same level can then be built, with $a_{ji} = 1/a_{ij}$.

The vector of weights is then obtained as the eigenvector associated with the largest eigenvalue of the criteria matrix (see [10] for a demonstration of why this holds).

The relative ranking of the alternatives is finally obtained by multiplying together the matrices that contain the weights of the elements of a level with respect to those of the level immediately above, from the bottom up.

[5] This particular scale is the result of psychological studies, which have shown that 9 levels constitute a good compromise between a detailed description and the “resolution capacity” of a person.

EXAMPLE 1

Let's consider the case of Fig. A.1, in which three stakeholders (the system operator, the generating companies and the environmentalists), three attributes (voltage drop, profit and environmental impact) and four alternatives (an overhead line, an underground cable, a transformer and a SVC) are represented.

As the attributes are not coherent (profit has to be maximised, while environmental impact and voltage drop have to be minimised), we have first of all to perform step 1 to transform the shareholders' desires into a homogeneous set of objectives. As a result, the three attributes to be maximised will be:

- profit (unchanged from the previous step);
- quality, which, for our purposes will be defined as the inverse of voltage drop;
- acceptability, which, broadly speaking, will be the inverse of environmental impact.

On the other hand, the fact that profit and quality will be typically expressed on a quantitative scale, while acceptability will be typically expressed on a qualitative scale, will not be relevant for AHP, as the method can treat both kinds of scales. The resulting AHP hierarchy is represented in Fig A.2. In this example, like in the ones that will follow, we suppose that the final decision is taken by a superior authority, which could be the government or, more probably, the Regulator.

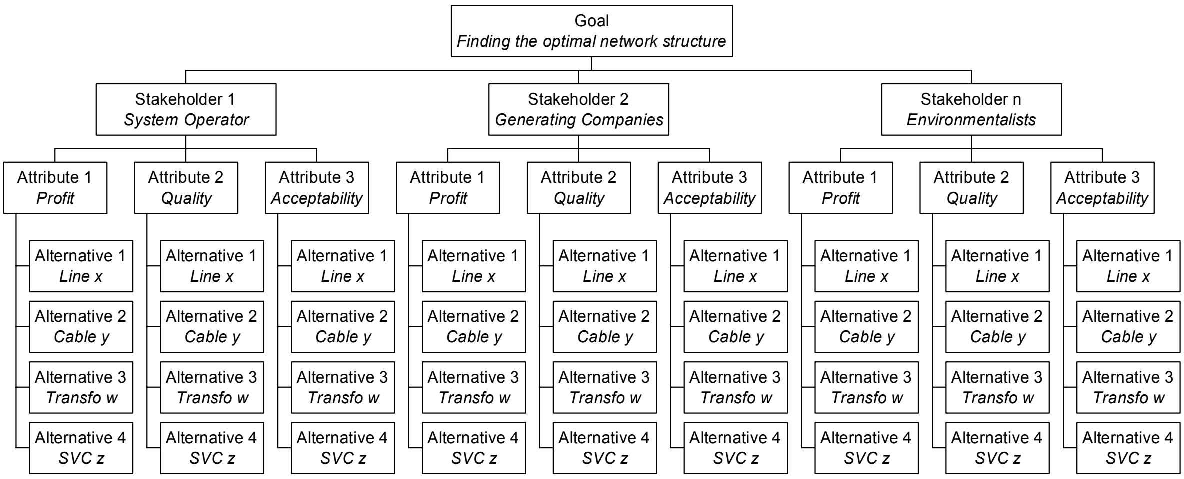


Figure A.2 AHP hierarchy

Suppose that the first level comparisons have led to the following matrix and vector of weights:

Goal	SysOp	GenCos	Envir
SysOp	1	1/5	1/7
GenCos	5	1	1/5
Envir	7	5	1

Goal	Weight
SysOp	0.07
GenCos	0.22
Envir	0.71

Suppose then that the results of the comparisons for level 2 are:

SysOp	Profit	Quality	Acceptability
Profit	1	1/9	1
Quality	9	1	9
Acceptability	1	1/9	1

SysOp	Weight
Profit	0.09
Quality	0.82
Acceptability	0.09

GenCos	Profit	Quality	Acceptability
Profit	1	9	9
Quality	1/9	1	1
Acceptability	1/9	1/9	1

GenCos	Weight
Profit	0.82
Quality	0.09
Acceptability	0.09

Envir.	Profit	Quality	Acceptability
Profit	1	1	1/9
Quality	1	1	1/9
Acceptability	9	9	1

Envir.	Weight
Profit	0.09
Quality	0.09
Acceptability	0.82

and those of the comparisons for level 3 are[6]:

Profit	Line x	Cable y	Transfo w	SVC z
Line x	1	2	3	4
Cable y	1/2	1	2	3
Transfo w	1/3	1/2	1	2
SVC z	1/4	1/3	1/2	1

Profit	Weight
Line x	0.47
Cable y	0.28
Transfo w	0.16
SVC z	0.09

Quality	Line x	Cable y	Transfo w	SVC z
Line x	1	3	5	2
Cable y	1/3	1	2	1/2
Transfo w	1/5	1/2	1	1/3
SVC z	1/2	2	3	1

Quality	Weight
Line x	0.48
Cable y	0.16
Transfo w	0.09
SVC z	0.27

Acceptability	Line x	Cable y	Transfo w	SVC z
Line x	1	1/7	1/5	1/9
Cable y	7	1	1/3	1/7
Transfo w	5	3	1	1/5
SVC z	9	7	5	1

Acceptability	Weight
Line x	0.04
Cable y	0.12
Transfo w	0.20
SVC z	0.64

The optimal solution would finally be obtained by multiplying the following matrices:

	Profit	Quality	Accept.
Line x	0.47	0.48	0.04
Cable y	0.28	0.16	0.12
Transfo w	0.16	0.09	0.20
SVC z	0.09	0.27	0.64

*

	SysOp	GenCos	Envir.
Profit	0.09	0.82	0.09
Quality	0.82	0.09	0.09
Accept.	0.09	0.09	0.82

*

	Goal
SysOp	0.07
GenCos	0.22
Envir	0.71

[6] Although we have introduced costs in the pairwise comparisons here, Saaty suggests that, in complex decisions, cost should be set aside until the benefits of the alternatives have been evaluated, and then a cost-benefit analysis should be performed.

The solution suggested by AHP would thus be the SVC:

	Goal
Line x	*.21*
Cable y	*.17*
Transfo w	*.17*
SVC z	*.45*

In his book, Saaty gives a complete example of how a US Utility, which must satisfy its investors, its clients, its suppliers, the regulator, the Department of Energy and the Environmental Public Agency, which all have different and conflicting objectives, can use AHP to balance all these contrasting objectives.

The main advantage of this method is that it provides a consistent scale to compare the different alternatives. However, like the classical method, it doesn't describe completely how a stakeholder feels about a project, because the result ends up being a weighted average of preferences, with no "non linearities" allowed.

The TOPSIS method
TOPSIS is an acronym for Technique for Order Preference by Similarity to an Ideal Solution. The principle of this method consists in selecting the alternative at the closest distance to the ideal solution; the ideal solution is defined as the imaginary alternative having, for each criterion, the best possible value.

The evaluation of an option x is done by calculating its Euclidean distance from the imaginary "ideal option" x^+, whose coordinates are the best scores in each criterion. The calculation of this distance includes also the imaginary "worst option" x^-, whose coordinates are the worst scores in each criterion, and a set of weights calculated with one of the methods of paragraph 4.5 or with the AHP:

$$D(x) = \sqrt{\sum_{i=1}^{n} w_i^2 \left(\frac{c_i(x^+) - c_i(x)}{c_i(x^+) - c_i(x^-)} \right)^2} \qquad \text{(A.3)}$$

EXAMPLE 2

Suppose we have four alternatives and three stakeholders, each with one criterion only:

	Stakeholder 1: SysOp Criterion: voltage drop	Stakeholder 2: GenCos Criterion: profit	Stakeholder 3: Environmentalists Criterion: Env Impact
Line x	5%	125m€	Very high
Cable y	8%	130m€	Medium
Transfo w	10%	150m€	High
SVC z	7%	95m€	Light

After step 1 (involving in this case a normalisation of costs, inverting and normalising voltage drop and converting environmental impact into a feasibility index, on a 1 – to 10 scale), the performance matrix becomes:

	Stakeholder 1: SysOp Criterion: normalized 1/voltage drop	Stakeholder 2: GenCos Criterion: normalized profit	Stakeholder 3: Environmentalists Criterion: normalized acceptability
Line x	10	8.3	2
Cable y	6.25	8.67	6
Transfo w	5	10	4
SVC z	7.15	6.3	8

In our case, the best option is $x^+ = 10, 10, 8$ and the worst option is $x^- = 5, 6.3, 2$; supposing that the set of weights is $w_1 = 0.2$, $w_2 = 0.5$, $w_3 = 0.3$, we obtain:
$D(x) = 0.378$, $D(y) = 0.252$, $D(w) = 0.283$, $D(z) = 0.513$
and the option closest to the ideal solution is cable y.

Like the classical and the AHP method, TOPSIS provides a unique solution, which "mediates" between the desires of the different stakeholders.

The ELECTRE methods
Unlike the methods we have described up to now, the results of the ELECTRE methods do not comprise an exhaustive classification of the options, with a numerical value provided to indicate the “performance” of each of them.

Rather, they identify a subset of options that globally do better than the others (or, in the ELECTRE jargon, “outrank” them), but are incomparable between themselves. Therefore, more than one alternative can be selected as optimal by ELECTRE.

This drawback is compensated by a much better description of the preferences of each stakeholder; in fact, the methods described up to now give a very limited insight into the real preference structure of a stakeholder. For example, some stakeholder may have a veto level, below which he or she is unwilling to go even when his or her weight is very low; or a stakeholder may be indifferent between two alternatives when they have very similar performances.

The father of these methods is B. Roy of the LAMSADE (Laboratoire d'Analyse est de Modélisation des Systèmes pour l'Aide à la Decision of the Université Paris Dauphine in France [11]).

ELECTRE I consists of performing a series of tests (“dominance”, “concordance condition”, “veto threshold”,…) on all possible couples of options and their consequences, so as to determine whether one outranks the other, or if they are incomparable (when no outranking is possible).

Let's consider two alternatives *x* and *y*; we consider that the statement “*x* outranks *y*” is verified if:

- the set of criteria consistent with the statement “*x* outranks *y*” is large enough and its weight is important enough (this is a sort of relaxation of the Pareto condition, also called “weak dominance”);
- the set of criteria not consistent with the statement “*x* outranks *y*”, that is to say those for which *y* is preferred to *x*, does not include any unacceptable element.

These two conditions can be expressed in mathematical terms by introducing:

- a concordance index, which measures the relative importance of the stakeholders' desires consistent with the statement "*x* outranks *y*":

$$C(x,y) = \frac{\sum weights\ w_i\ \ such\ that\ u_{si}(x) \geq u_{si}(y)}{\sum weights\ w_i} \tag{A.4}$$

  where the w_i are obtained by the usual methods;
- a normalised discordance index which measures the regret a stakeholder feels when alternative *x* is chosen instead of alternative *y*; this allows the definition of a limit such that, if the difference $u_{si}(y) - u_{si}(x)$ is greater than this limit for at least one of the stakeholders, the statement "*x* outranks *y*" cannot be accepted whatever the strength of the concordance index:

$$D(x,y) = \frac{\max_i \left(u_{si}(y) - u_{si}(x)\right)}{100} \tag{A.5}$$

  One should notice that, in order to keep the things simple, we have supposed that the intensity of the disagreement with the statement "*x* outranks *y*" can be measured in the same terms for all the stakeholders; however, a discordance index for each stakeholder could be introduced.

These concordance and discordance conditions allow the outranking relationships between alternatives to be defined and represented on a graph.

The nodes of this graph are the alternatives and the arcs represent the outranking relationships; the arc (*x*,*y*) will thus appear on the graph only if:

$$C(x,y) \geq p \quad and \quad D(x,y) \leq q \tag{A.6}$$

where *p* and *q* are threshold values (preference level and indifference level).

The solutions suggested by ELECTRE I will finally be the kernel of the graph, that is to say the set of alternatives, which are not outranked by others, and therefore are incomparable between themselves.

The method we have described is the simplest one (!) in the family of the ELECTRE methods; improvements of this method, such as ELECTRE IS or ELECTRE III, use an even more detailed description of the desires of a stakeholder, for example by introducing veto thresholds or more sophisticated criteria.

EXAMPLE 3

Suppose we have four alternatives and three stakeholders, each with one criterion only.

After step 1 (involving in this case a normalisation of costs, inverting and normalising voltage drop and classifying environmental impact on a 1 – to 10 scale), the performance matrix becomes:

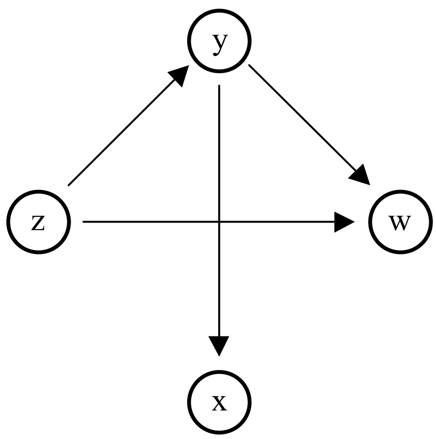
	Stakeholder 1: SysOp Criterion: normalised 1/voltage drop	Stakeholder 2: GenCos Criterion: normalised profit	Stakeholder 3: Environmentalists Criterion: normalised acceptability
Line x	10	7	1
Cable y	5	8	8
Transfo w	4	10	7
SVC z	7	5	10

Let's suppose the of weights are $w_1 = 0.2$, $w_2 = 0.5$, $w_3 = 0.3$; the concordance and discordance indexes are then:

	Line x	Cable y	Transfo w	SVC z
Line x	-	1	1	3
Cable y	4	-	3	2
Transfo w	4	2	-	2
SVC z	2	3	5	-

	Line x	Cable y	Transfo w	SVC z
Line x	-	7	6	9
Cable y	5	-	2	2
Transfo w	6	1	-	3
SVC z	3	3	5	-

If we use a concordance threshold p=3 and a discordance threshold q=5 (which means, roughly, that x should be "much better" than y in at least 3 important criteria and no attribute of y should be significantly better than the corresponding attribute of x by more than 5 units), the outranking graph is:



For the values of concordance threshold used in this example, the kernel of the graph, and thus the best solution, is project z.

The greatest advantage of these methods is that they represent the desires of the different stakeholders in great detail. However, in situations more complex than the simple example above, the core is usually composed of more than one element; the quest for the final solution thus stays open. Another drawback of these methods is that no quantitative information is provided to indicate by how much the project z is better than the others. Moreover they can be too complex to be presented to non-specialists and the setting of the parameters might be tricky.

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