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An integrative modelling approach for understanding competitive electricity markets

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A model of the UK Electricity market is presented focusing on the competitive behaviour of buyers and sellers. The model was developed using the OO/DEVS object oriented industry simulation platform and includes as components: generators, suppliers, customers, the electricity pool and the contract market. The motivation and structure of the OO/DEVS platform is described both as a vehicle for systems thinking and as an architecture for integrative modelling, allowing, for example, optimisation and spreadsheet models to exist as objects within an overall strategic simulation model. The actual case-study implementation presented in this paper, was undertaken in collaboration with one of the privatised utilities in the UK.

Keywords: model integration; object oriented modelling; strategic simulation; electricity

Introduction

The 1990s are becoming a decade of fundamental change for electricity industries worldwide. Major structural changes are being driven both by the need to increase competitiveness and efficiency in mature economies and to stimulate independent investment in developing countries. Measures adopted include deregulation, open access to markets, unbundling of generation, transmission and distribution, creation of electricity pools, and the full privatisation of the industries. Countries such as Chile, Argentina, Norway, New Zealand and the UK have led these reforms, but many other countries such as Finland, Portugal, Philippines, Colombia, Brazil, India, Thailand, Australia and the US are following. In all cases, change is being driven by an economic ideology and faith in market forces, and as a consequence the conventional methods of central electricity planning are becoming less relevant.[1,2]

In practice, the introduction of competition has posed a number of new questions such as:

- What is the 'optimal structure' for the electricity industries that maximises competition without compromising reliability of supply?
- How can private and public electricity companies be best regulated, so that the right incentives are provided, but also the benefits of competition are shared fairly by investors and the public?
- How can companies cope with the increased uncertainty and risks of deregulated electricity markets?

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In a previous paper,[3] we discussed the implications of such questions for OR practice and presented a *Complementary Modelling* approach to assess the transfer of ownership effects of electricity privatisation (rate of return, capital structure and tax implications) and to analyse the competitive structure of the market (investment incentives, regulatory effects, impact of risk and competing strategies). The 'softer approach' of system dynamics was used alongside a detailed optimisation model in order to incorporate various perspectives of strategic and regulatory behaviour. Whereas the optimisation model facilitated the understanding of capacity mix, the systems model indicated how cycles in the reserve margin might evolve. Whilst the deterministic optimisation model was effective in giving relative generation costs, the system model helped to develop scenarios in which competitive market behaviour could evolve and influence the decision-making in the industry.

This mixture of optimisation and simulation models used side-by-side provided useful complementary insights but had its own limitations. From the perspective of model management theory (see for example References 4 and 5), the integration between the models is clearly ad hoc and very restricted. Furthermore, the decision makers from the electricity industry working with us in joint projects soon began to require a greater level of modelling detail. Given the lack of modularity, it became difficult to extend the models in order to address new issues such as the interaction between the electricity pool and the contract market or the relationships between the gas and electricity markets.

These limitations of the complementary modelling approach prompted the development of a new modelling platform OO/DEVS based on **O**bject **O**rientation and the **D**iscrete **E**vent **S**pecification Formalism.[6] The motivation was to develop a modelling platform that could provide the kind of industry simulation functionality which has made system dynamics increasingly popular in strategic modelling applications[7–10] and at the same time fully integrate with other modules performing functions such as detailed optimisations and spreadsheet-based financial planning. In addition, the development of OO/DEVS aimed to address some of the methodological criticisms of system dynamics, related to such features as 'structure' (modelling generalisation and aggregation relationships within a model), 'focus' (modelling sufficient level of detail), 'reusability' (creating reusable model components), and 'time-representation' (continuous rather than discrete time steps).[6] A prototype OO/DEVS and its graphical user interface was implemented in the Smalltalk programming language.[11]

In this paper, we describe how OO/DEVS was applied in practice with a team of analysts working at one of the UK Regional Electric Companies (which has to remain anonymous and is referred to here as 'REC'). The project was undertaken over a 12 month period and some aspects of the group facilitation as well as the modelling details are described below. The next section reviews the OO/DEVS modelling platform, followed by a description of the Electricity Markets Model, concluding with a commentary on its impact within the company and an illustration of the types of strategic insights which were obtained.

Object oriented/DEVS: an overview

OO/DEVS is a simulation platform that has been designed and developed as a fundamental extension to System Dynamics for industry modelling and simulation. The philosophy of modelling with OO/DEVS is consistent with that of systems thinking, but, in terms of the modelling process, OO/DEVS adopts and implements object oriented design. Also, in terms of the time representation OO/DEVS is based on the Discrete Event Specification Formalism (DEVS[12]). Ninios *et al*[6] provide a detailed description of OO/DEVS and compare this approach to system dynamics. In Ninios *et al*[11] the implementation of OO/DEVS is presented within the Smalltalk computer language. Here only a summary of the main features is therefore provided:

- *Entity based Modelling*: OO/DEVS allows the modeller to think and model the industry in terms of the main players, their strategies and the way they interact. Each player can be viewed as an object with specific attributes and methods that represent decision rules. The OO/DEVS paradigm allows this natural type of thinking to be directly mapped into a representation that can then be simulated.
- *Object Oriented concepts*: The platform fully supports object oriented model design and development concepts such as encapsulation of data and behaviour into classes, inheritance, polymorphism and message passing.
- *Aggregation/Disaggregation*: The ability to construct composite (coupled) models from a set of simpler ones allows the modeller to develop detailed decision support systems by modelling the required level of detail. At the same time a strategic 'view from above' can be maintained by monitoring the behaviour of coupled models, at different aggregation levels. A graphical representation of the model structure is provided by the Model Decomposition diagram in which the user can 'zoom' in and out with ease.
- *Integration of 'hard' and 'soft' modelling approaches*: Complex decision rules can be implemented as external OR models that are activated during the simulation and effectively become parts of the model. For example the workings of the electricity pool were modelled as an optimisation model. In addition OO/DEVS can integrate with spreadsheet or database models and communicate interactively with them.
- *Time representation*: The platform provides a concise way to represents time as events within the system and furthermore to bound decision rules (that are object methods) to time.
- *Separation of models and simulation engine*: This is achieved through generic simulator modules that are attached to models prior to the start of the simulation without user intervention. In designing and developing models the user does not need to be aware of the inner workings of the simulation engine. This is particularly attractive because it provides the basis for treating models as knowledge and creating model-bases.
- *Modularity, reusability, extensibility*: Due to the separation of models and simulation engine, objects can be stored in a model base. In addition, inheritance and encapsulation provide the means of extending, modifying and reusing old model components.
- *Graphical Model Specification*: The approach lends itself to extensive use of graphical model specification, manipulation and synthesis. Therefore, we have devised three types of diagram, the *Class Hierarchy Diagram*, the *Model Decomposition Diagram* and the *Level Diagram* that jointly provide a complete specification of a model. Examples of these diagrams are provided in section 3.2.

The electricity markets model

Following privatisation in 1990 the UK electricity industry was unbundled into separate generation, tr nsmission, distribution and electricity retailing (referred to as 'supply' in the UK) activities. Transmission and distribution remain private regulated monopolies, but there is growing competition in the generating and supply markets. Initially, the distribution companies had a monopoly of the supply to commercial and residential customers in their regions, but that has progressively been eroded. A key element of the unbundling was the separation of physical supply through the natural monopolies of distribution and the business activities of electricity retailing to end-users. Initially, two private generators (National Power and PowerGen) a public nuclear company (Nuclear Electric) and twelve private distribution & supply companies (called Regional Electric Companies, 'RECs') competed alongside a growing number of small independent generators and suppliers. Given the innovative new structure of the industry, there has been international interest in the evolution of the market structure and its implications for efficiency and electricity prices.

In this new industry structure, two distinct markets for buying and selling electricity have emerged. The first is the pool market, that produces day-ahead electricity prices on a half-hourly basis and the second is a contract market, in which pool price risk can be hedged. Electricity contracts can be conceived as financial instruments with a cash-flow determined by reference to the pool. The main suppliers of contracts are electricity generators, and the main buyers have been the twelve RECs. RECs are simultaneously buyers and sellers of electricity contracts. They buy contracts from existing or the new independent generators and they sell contracts to large customers. As a result, a secondary contract market has been created, between non-franchise customers (large customers eligible for contracts) and electricity suppliers.

The modelling project described in this paper took place within a division of the commercial department of one of the UK regional electricity companies (referred to here as the REC). One of the main concerns of this division is the development of medium (six to twelve months) to long term (up to 10 years) scenarios of the evolution of the electricity industry. The issues under consideration include the evolution of the pool and contract markets, competition, investments and regulation. Given the fact that the structure of the industry was fairly recent, it was clear that the plethora of issues and scenarios which could be explored was formidable. One of the reasons REC became interested in OO/DEVS was its potential reusability, compared to the discardable nature of traditional systems dynamics models. Another, was the ability to integrate within OO/DEVS existing optimisation models and to dynamically communicate with spreadsheet based financial models.

The modelling team was composed of a number of managers and analysts whose prior background was engineering, in terms of education, while their modelling expertise consisted mainly of 'hard' Operational Research techniques (optimisation and forecasting) and spreadsheet modelling. Even though the team had been using programmers to implement mathematical models, little or no knowledge of software engineering existed within the modellers.

The project was initiated by introducing to the modelling team the OO/DEVS modelling platform and simulation engine. Initially, when the first ideas associated with OO/DEVS were presented to the company, they were met with some scepticism and misunderstanding. In order to alleviate these problems a number of tutorial sessions were organised which aimed at familiarising the modelling team with systems thinking, object orientation and discrete event simulation as well as the overall mechanics of model building within OO/DEVS, through a series of model building exercises.

The next step was the development of a model of the electricity purchasing and selling policies within the industry (the Electricity Markets Model) jointly with this team, through regular model building meetings (once or twice a week for a period of four months) at the RECs offices, while a significant amount of background work was performed in-between meetings, both at the London Business School and at the REC. It is interesting to observe that during this process, the initially sceptical management team became owners of the model and advocates of the approach, which they themselves then presented to higher management and directors.

The modelling process

One of the principal aims during the modelling exercise was to assure that the corporate modelling team felt ownership of the framework and its underlying concepts. The key in doing so, was to build a model jointly with the academic researchers undertaking the role of facilitators as much as model builders. Below we list the main stages that were followed in the model building process.

Step 1: Identify the issues of interest and the general industry background in relation to these issues. In our case, this step was carried out through fairly unstructured brainstorming sessions.

Step 2: Identify the main entities (objects) in the system to be modelled. These entities may be physical entities (for example generation companies), aggregates of physical entities (for example the customers of the electricity industry), or notional entities which nevertheless have a specific function in the system (for example the contract market). The Model Decomposition Diagram (Figure 1) is used as a tool during this process.

Step 3: Select the functional areas of interest within the objects in the previous step. This is the process of specifying the model boundary, by discarding any areas of the system, that are not interesting or relevant to the issues in hand. The process leads to the identification of the variables of interest within each object, as well as the broad behaviour of the object.

Step 4: Having identified the objects in the problem space and their detailed behaviour, it is important to identify the useful generalisation/specialisation relationships among them by recognising common behaviour. The objective is to achieve a sufficient level of abstraction, in order to either identify (in the model base) objects previously built, or to build new reusable model components. The outcome of this step is the Class Hierarchy Diagram (Figure 2).

Step 5: Specify the way that the objects, within the system in hand, influence each other. This process, effectively corresponds to the identification of information and material flows, which is also used in system dynamics. The Level Diagram (Figure 3) may be used as a tool during this step. The facilitator/modeller can start with a Level Diagram containing only model entities and a discussion can be carried out on how these entities interact with each other.

Step 6: Specify the decision rules of the objects within the model space. This step requires the detailed description of 'the way that our objects get things done' and may bring us back to step 2 as more 'secondary' objects might be identified.

Step 7: As soon as the software representation of the model components is built and tested, a model can be put together and simulated. Steps 1–6 can be repeated within the OO/DEVS environment, so that alternative model structures can be tested.

The process of model building is highly iterative, as the modeller (or sometimes the user) can move back and forth on the steps of model building, experimenting with the structure of the model. For a discussion of the use of the OO/DEVS diagramming model representations, namely the Model Decomposition the Class Hierarchy and the Level Diagrams, see Ninios *et al.*[11] The examples of the diagrammatic views of the Electricity Markets model shown in Figures 1–3 are explained in the next section.

Whilst the above seven steps reflect our model building experience within OO/DEVS, it should be pointed out that they are by no means the only way of approaching knowledge elicitation and model building within the platform. Areas like cognitive psychology, small group processes and system dynamics have approached the problem of knowledge elicitation from many perspectives[13–15] and can possibly offer a number of useful techniques that can be blended with the above process. Indeed, the proposed seven steps contain ideas already found in the fore-mentioned areas. For instance cognitive psychologists (for example see Hackman and Morris[16]) have distinguished three main types of cognitive tasks: eliciting information, exploring courses of action, and evaluating situations. Step 1, corresponds to the first of these cognitive tasks, which within the SD community is referred to as brainstorming. Step 2, is very similar to Duke's[17] structured workshop technique according to which the participants write down on small pieces of paper all concepts that come to mind when thinking about the policy problem under study. This step also draws from the Object Behaviour Analysis approach[18] for object oriented design. Step 3, is similar to what SD modellers refer to as deciding what variables may be included or excluded from the model's boundary. Step 5 corresponds to the definition of the way that objects collaborate in the 'responsibility driven' approach.[19]

The model structure

After many deliberations taking into account the company's priorities, a number of questions were formulated that included the following:

- What is the long term impact of developments in the electricity pool on the contract market?
- How will the competitive position of the regional electricity companies be affected by the imminent opening of the market to competition?
- To what extent can generators manipulate the Pool through different tactics in bidding their plants to the Pool?
- What is the impact of a large number of gas and coal take-or-pay fuel contracts on pool and contract prices?
- How will the total benefits in the system be allocated between different parties?
- What is the effect of abrupt changes in circumstances?

Given the issues under consideration the modelling team suggested the following model components (objects), some of which are aggregate objects:

- The *Electricity Generation* side was decomposed into four generating companies National Power, PowerGen, Nuclear and a fourth entity representing the independent power producers (IPPs) within the industry.
- The *Supply* side was decomposed into four groups of regional electricity companies distinguished by (a) a different electricity purchasing approach, and (b) a different customer targeting approach.
- The *Customer Side* was broken down to three types of customers: (a) the below 100 kW market, which roughly corresponds to the domestic market, (b) the market that corresponds to the range of 100 kW–1 MW, and covers commercial load and small industry and (c) the market over 1 MW which corresponds to the large industrial customers.
- *The Electricity Pool Market*. The Electricity Pool produces half-hourly electricity prices for the day ahead, based on plant bids submitted by the generators and forecasts of electricity demand. In this model, since we are interested in medium to longer term interactions,

an aggregate view of the pool is taken in which price calculations are carried out based on load duration curves.

- *Contract Markets*. Electricity contracts are financial instruments that provide hedging for electricity price risks. The main market of electricity contracts is between generators and suppliers. A second market was identified that includes transactions between suppliers and customers. We called this market 'Customer Contract Market'. In reality the contract markets are very complex, with a large number of distinct products traded bilaterally between generators, suppliers and customers at different time intervals. In the model the markets were viewed at an aggregate level, by constructing supply and demand curves for the contracts and finding the equilibrium as explained in section 3.3.

Figure 1 depicts the model decomposition diagram constructed by the modelling team. In this diagram, a link from an upper level (for example *Generators*) to a lower level (for example *National Power*) can be interpreted as '*National Power* is part of the *Generators*'. This structure allows a change of focus of the level of detail, in browsing the model, by 'zooming' in or out. The next step (Step 3), was to identify and specify the required attributes and behaviour of the different entities, and therefore set the system boundary. The modelling team identified that the generators own plant, bid their plants to the pool, and offer electricity contracts to the buyers of electricity (regional electricity companies). The electricity pool receives the bids, produces plant schedules, and determines electricity prices. The regional electricity companies buy contracts from the generators, buy electricity from the pool and offer contracts and tariff prices to the customers. Finally, the customers (consumers of electricity) buy electricity, either through contracts from any of the electricity suppliers, or by paying the tariff price to their local regional electricity company.

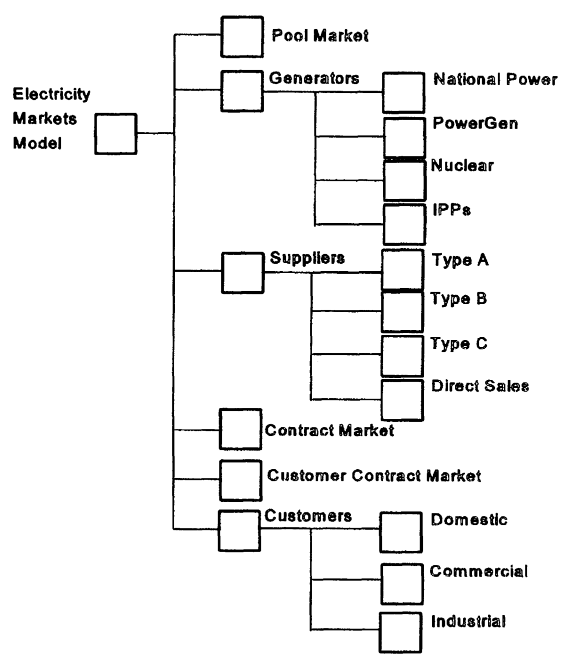

Figure 1 The electricity markets model decomposition diagram.

It should be mentioned, that an 'Object Specification Form' was used to document the above process. This form constitutes the specification of each object's public and private behaviour, instances, variables, collaboration with other objects in the system and message specification. Such type of form is quite common to many object oriented design methods, and was felt that the modified version of it, adapted for OO/DEVS, helped considerably in developing the model objects and eased the transition to the coding of the model. An example of such a form for the entity Generator is given in Table 1.

By studying the required functionality of the objects in the Model Decomposition Diagram, a number of object classes were generated. In creating these classes, common functionality and characteristics can be captured by general classes, from which more specific classes can be derived. The derived class hierarchy is depicted in Figure 2. All classes are subclasses of the basic entity class *TModel*, that contains the essential simulation capability.

A class *Company*, was suggested to capture the common characteristics of all companies, within the model. It was decided that these characteristics should include the maintenance of profit-and-loss and balance sheet data. Generation companies and RECs are specialisations of the class *Company* derived by adding functionality to this class. It was suggested that generators would be defined as instances of a class *Generator*, or its subclasses (IPPs and Nuclear were modelled as separate classes to reflect certain

Table 1 Object specification form (partial) for object generator

Object name: Generator *Inherits from*: Company	
Public behaviour: Plant bids Supply contracts	*Variables*: plants file, supply, plants, sales contracts, bids, capacity, utilisations, smps, mark ups, coal deal, non market contracts
Private behaviour: Formulate plant bids Formulate supply contract preferences	
Instances: (4 instances) National Power and PowerGen, 2 more instances of two subclasses: IPP and Nuclear	
Collaborates with the object: Supplier, supply curve, plant, contract market, pool market	

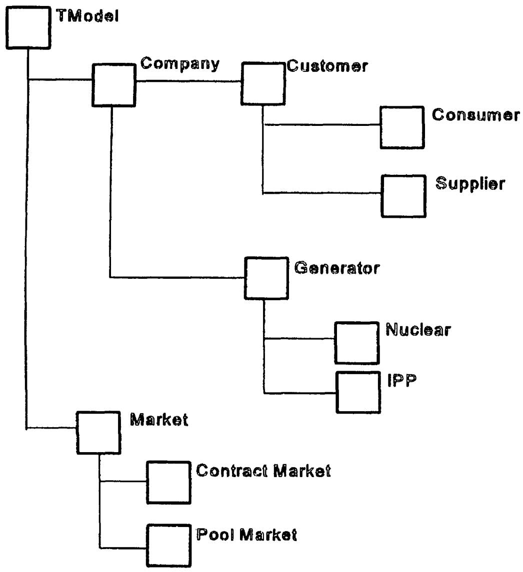

Figure 2 The class hierarchy diagram.

differences in their bidding and contracting strategy). The RECs were defined as instances of the class *Supplier.* It should be noted that subclasses inherit the behaviour of their parent classes. For example the class *Nuclear* inherits all the behaviour of the class *Generator* and only alters a small part of it. In this way inheritance facilitates code reuse.

Finally, the pool and the contract market were designed to be subclasses of a class *Market*, which models the function of balancing demand and supply and thus producing the price for a product. Two instances of the class *Contract Market* were used in the model, in order to reflect the existence of the contract market between Generators and Suppliers, as well as the existence of a secondary contract market between the Suppliers and the Customers (the *Customer Contract Market*).

Following the specification of the model decomposition and the class hierarchy diagrams, the modelling team went to Step 5 to define the influences between the different entities. This can be done by dissecting the system decomposition hierarchy at different levels and showing the influences using the Level Diagram.

Figure 3, for example, shows the interactions at the highest level. At this level *Generators* is the aggregation of all generators and *Suppliers* is the aggregation of all major electricity suppliers (regional electricity companies). *Customers* represents the aggregate of the three types of customers. The *Pool Market* balances demand and supply for electricity and determines electricity prices, while the *Contract Market* balances demand and supply for different types of contracts and determines contract prices. In addition, the *Customer Contract Market* balances supply and demand for contracts between the Customers and the Suppliers.

It can be observed that the *Generators* influence the *Pool Market* by bidding their plants at specific prices, and the *Contract Market* by supplying contracts. The *Pool Market* schedules the plants and produces electricity prices, which are fed back to Generators as well as to Suppliers and Customers. The Suppliers, influence the *Contract Market* through their demand for contracts, and the *Customer Contract Market* through a supply of contracts. They also influence the Customers with their tariff prices. The *Custo-*

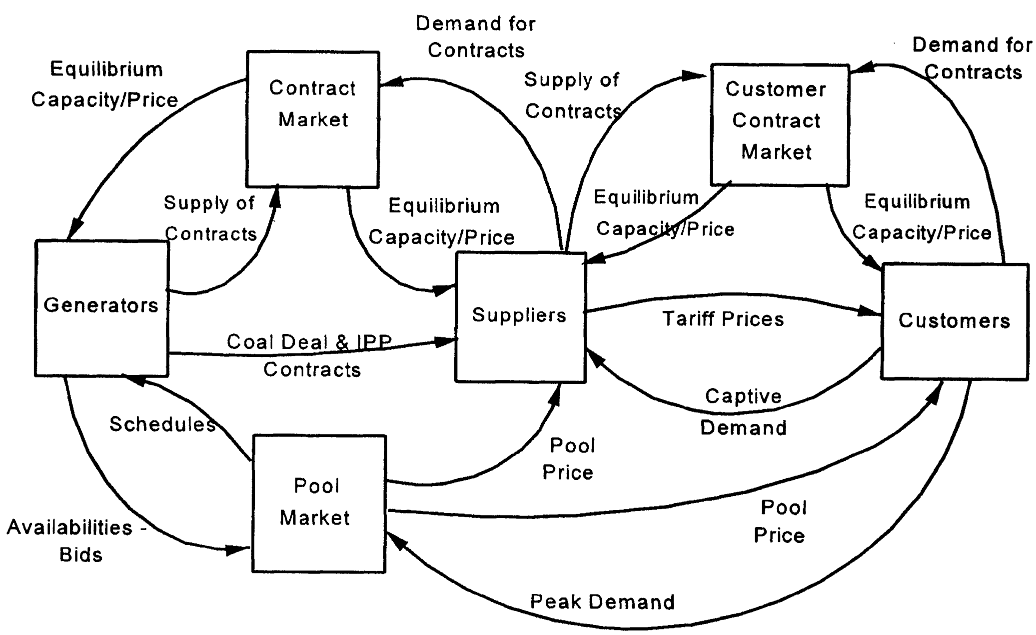

Figure 3 The level diagram—top level.

mers, finally, influence the *Customer Contract Market* through their demand for contracts, and the suppliers through their demand for actual electricity.

Step 6 was probably the most important part of the model building process, as the behaviour of the different entities was modelled in very elaborate decision rules, including a significant amount of 'hard' data, as well as 'soft' information based on the mental models of the team. This step is discussed in detail in the next section.

The decision rules

The specification of behaviour is necessary for the construction of computerised OO/DEVS models that can be simulated meaningfully. As pointed out in previous work,[11] OO/DEVS is very flexible when it comes to specifying behaviour (decision rules). The user may construct equations, logical rules, time-related events or even external algorithms for carrying out complex calculations.

The electricity pool market. The electricity pool balances demand and supply for electricity and calculates electricity prices. On a daily basis, a day-ahead plant schedule is calculated based on generators' bids and forecast demand. In this model, since we are interested in medium to longer term interactions, an aggregate view of the pool is taken. The pool price calculation is carried out using the well validated ECAP[20] production costing algorithm.

In this algorithm, annual electricity demand is approximated by eight seasonal load duration curves. Given a set of plants, their bid prices, availabilities and take-or-pay constraints, as well as the demand profile, the ECAP algorithm generates the optimal production schedule and produces pool prices for each season of the year. Such a representation of the Pool Market is necessary, as it provides an accurate model of plant economics in the system, which is the basis for exploring realistically the strategic behaviour of the electricity companies.

This part of the model demonstrates effectively the model integration aspect of OO/DEVS in that it allows an optimisation based module to be included as a decision rule of an object. In each simulation iteration the optimisation routine is executed and its results trigger further decision rules.

Electricity contracts and the contract markets. Apart from the model entities that we have already discussed the next most interesting object from a modelling point of view, was the object *Electricity Contract*, which is traded in the contract market. In reality the contract market is very complex, with a large number of distinct products. The basic type of contract is a two-way contract that requires (a) the seller to pay the buyer the difference between the pool price and a reference price (the strike price), whenever the pool price exceeds the strike price, or (b) the buyer to pay the seller the difference between the strike price and the pool price whenever the latter is lower. The overall effect is that both parties are provided with a fixed price equal to the strike price, for electricity purchased under the contract. A variation of a two-way contract is the one-way type, which requires the seller to pay the buyer the difference between the pool price and an agreed strike price for an agreed number of units whenever the pool price exceeds the strike price. This type of contract effectively caps the buyer's electricity cost (see also James Capel & Co.[21]).

An electricity supply contract is usually based on a given amount of capacity (MW) for which the buyer often pays a fixed fee, the option fee. There are also minimum and maximum take constraints on the number of hours the contract can be exercised. In this respect we can identify base load and peak load contracts. The former have a low strike price and a high minimum take, whereas the latter have high strike price and low minimum take. Contracts can also be profiled in such a way that the contracted capacity varies throughout the contract duration. These contracts can offer customised type of cover.

The duration of contracts may vary. On the one side of the spectrum, we have the contracts signed by the regional electricity companies with independent power producers (IPPs), which are in general long term (10–15 years), as well as the contracts which required the regional electricity companies to buy a large part of the output of plants which were themselves contracted to buy the output of British Coal until 1997/98.[22] These contracts still exist after the sale of British Coal mines to private companies. On the other hand, we have the existance of short-term traded contracts (electricity futures arrangements or EFAs) with a duration of a few weeks. The vast majority of the contracts signed so far have durations of one year or longer and EFAs have played so far only a marginal role.[23,24]

Finally, most contracts link the strike price to various escalators, mainly fuel prices and inflation (RPI). Table 2 summarises the important dimensions that characterise contracts. Due to the complexity of the contract market, various simplifications were necessary, whilst maintaining the main features of the market. Different annual contracts were grouped into three contact types, base, medium and peak load according to the take-or-pay conditions. In addition, the long-term contracts with independents and the coal contracts that have pre-determined price and duration

Table 2 The main dimensions of electricity supply contracts

Capacity	No. of MW, min/max take, base/medium/peak load, profiling
Payments	Option fee, strike price, one-way, two way
Load	Base-medium-peak, take-or-pay, profiling
Duration	Long term (IPP contracts), coal deal, short term
Reference price	SMP, capacity component, uplift, combination of them
Indexation	Fuel prices, Retail Price Index

were included. For the annual contracts, generators would decide how many of each type they would be prepared to sell, at different prices. This in effect, is the supply curve for this financial product. Similarly, regional electricity companies and non-franchise customers would decide how much they are prepared to buy at different prices on the basis of their aversion to pool risk exposure (demand curve).

From a modelling perspective, class *Curve* was created as the superclass of two subclasses: *SupplyCurve* and *DemandCurve*. This class models the commonalities between the two types of curve, while the two subclasses model the specific characteristics of demand and supply. As a result a *Contract Market* was modelled as the object where supply and demand curves can be aggregated as they are submitted, demand and supply are balanced, and the equilibrium price is eventually calculated. This is a simplified but realistic approximation of the way that the market operates and clears.

Figure 4 illustrates the calculation of such a price. The price axis of the supply curve reflects the bid prices of the plants plus a contract premium. Each curve is composed by stacking up the plants in terms of price while the capacity axis contains the cumulative plant capacity. Plants are distinguished into the three fore-mentioned types of load in terms of their utilisation. For instance, plants that have utilisation of 60% or more compose the 'base load' curve, plants that have 20% or more utilisation compose the 'medium load' curve, while all plants compose the 'peak load' curve. Different equilibrium prices are calculated for each type of load.

The above view of contract modelling was attractive, because it proved a very versatile tool in modelling a wide range of supply curves (reflecting plant economics), as well as a wide range of demand curves (expressing demand preferences). Such curve representations allowed the modelling team to debate different levels of risk aversion on the part of distribution companies by shifting the demand curve upwards or downwards. Similarly, a squeeze of the contract market by the generators was modelled by

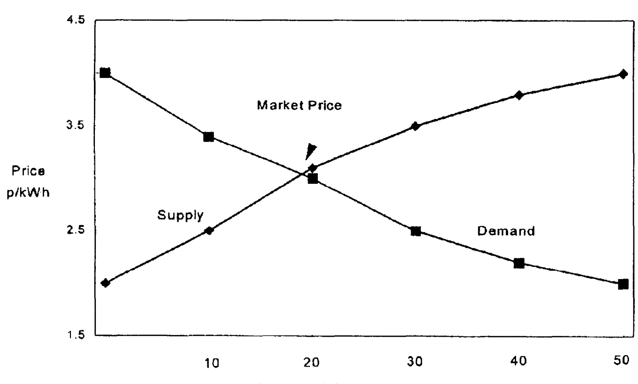

Figure 4 Aggregate supply and demand curves for contracts.

moving the supply curve for contracts upwards. Other types of oligopolistic behaviour were also considered. Regarding the *Customer Contract Market*, the *Suppliers* provide contracts which reflect the mix of their own contract and pool purchases, while the *Customers* (the Consumers of electricity) submit demand curves which reflect their willingness to contract for electricity.

The generators. Both PowerGen and National Power have relied upon contracts for their profitability. They initially pursued a dual track strategy. Firstly, they entered the supply business very aggressively, taking market share from regional electricity companies (we have modelled this fact through a supplier called '*Direct Sales*' which targets only the competitive market, and has no IPP or coal related contracts). Secondly, the threat of pool price volatility tended to set contract prices at levels higher than expected pool prices. In the supply business, RECs have a competitive advantage in that they already have the sales infrastructure that the generation companies lack and a long established relationship with their customers. However, the generators in trying to gain market share have to offer low prices. The overall effect is that prices decreased in those markets which have been opened to full competition.

The generators have many ways to influence both the pool and the contract markets. They can affect the pool market by employing bidding tactics, such as making plant unavailable to the pool or varying bid prices. They can also decide to offer more or fewer contracts at more or less attractive prices, provided they are non-discriminatory. All these possibilities need to be investigated. But as a starting point, our decision rule assumed cost reflecting bidding (cost + margin), and a contract supply curve that presumes willingness to contract most of their capacity. This reflects their publicly declared intentions, and indeed around 90% of the energy required has been traded under contract since 1991.

In terms of modelling, each plant in the system, is represented as an instance of the class *Plant*. This class encapsulates specific plant characteristics, such as its name, owner company, capacity, availability, utilisation, type of fuel, economic life, as well as starting and ending production date. As a result, each *Generator* owns a set of such objects. Prior to bidding its plants to the pool, each generator groups them into base medium and peak plants, using as a benchmark the previous year's plant utilisation. Based on this grouping, generators bid their plant to the pool adding a different mark up for each type of load.

Finally, investment and disinvestment have been included, as the generators in our model bring new plant into production or retire old plant capacity. This is achieved externally (i.e. there are no actual investment or retirement rules in the model) by specifying starting and ending production dates for each plant. Plant investments and retirements reflect the announced investment decisions of the generators.

The suppliers. In the beginning of each financial year the *Suppliers* (regional electricity companies) have to set tariffs and offer contracts to customers, based on estimates of what the pool price will be. Given the experienced pool price volatility, the risks of over or under-charging are very high. Undercharging could result in serious financial loses. On the other hand, overcharging franchise customers is penalised by regulation and overcharging non-franchise customer would result in losing these customers to competitors. The main role of electricity supply contracts has been to reduce and if possible eliminate this risk. RECs would prefer to be fully covered for their forecast demand, if the risk premium involved is not very high. The risk premium is measured as the difference between the cost of buying electricity through contracts and the expected cost of buying from the pool (net contract cost).

Cost stability is a key factor in achieving a number of other objectives such as increasing customer satisfaction, broadening the customer base, avoiding conflicts with the regulator and pleasing the shareholders. But cost stability is not the only objective in determining the level of cover and the composition of the contract portfolio. The cost of the cover is also an important consideration, despite the fact that regulation did allow RECs to pass this cost on to franchise customers. Electricity companies are competing with other energy companies and with each other, thus cheap energy supply will in the long run be a definite competitive advantage. In addition gross inefficiencies attract the attention of the regulator, since 'economic purchasing' was part of the licence requirements. RECs have also used supply contracts to influence developments in the generation market. By signing long term contracts with independent power producers they tried to reduce the oligopolistic power of National Power and PowerGen, which own most of the price setting plants, and they managed to establish a sizeable new competitive force in this market. The IPP contracts have been represented explicitly in the model.

Suppliers participate both in the pool and the contract market. In the pool Suppliers buy the electricity they need for their committed demand. In the contract market Suppliers purchase contracts to reduce the variability of their electricity purchase costs. Suppliers' preference for contracts was modelled through a demand curve for contracts. The initial decision rule is that if the net contract cost is zero for a particular contract, Suppliers are prepared to buy enough to satisfy their expected demand. For higher risk premiums, they are prepared to reduce the level of cover and take some pool risk. Required electricity purchases change each year as a result of their performance in the non-franchise customer market. Suppliers will formulate a view of their expected success in this market and use this, plus their captive market commitments to determine their purchasing targets from the Generators.

As mentioned earlier, the design choice was made to define different groups of suppliers in terms of (a) their purchasing behaviour (namely pool risk aversion in buying contracts) and (b) their selling behaviour (namely by offering different product ranges, for example some only offering to the captive market, others also offering to the non-franchise market, on different bases such as 'Pool + Margin', 'Fixed Price', 'Contract + Margin' etc). It should be pointed out that one of the instances of the class Supplier, represents the 'Direct Sales' companies set up by the Generators to compete in the Customers Contract Market (see Smith New Court[22], p. 29). As a result 'Direct Sales' do not have any coal deal or IPP contracts, and do not target domestic customers. The objective of introducing these types of supplier was to allow different commercial strategies to be compared. This was considered by our client as one of the key aspects of model development as the final model would show how different approaches would fare over the years in terms of market share and profitability.

The customers. The modelling team split the customers into the usual three sectors, namely 'Domestic', 'Commercial' and 'Industrial', with a further sub-division for each of the groups into a 'captive' part (known as franchise) and a 'competitive' (known as non-franchise). An initial allocation between captive and competitive is defined at the beginning of the simulation run, with subsequent changes year on year to reflect the development of the market. It was felt that this feature would provide an interesting dynamic element in the model. Customer demand is initialized to 50 000 MW (peak demand) for the first year of the simulation, and increases thereafter at a rate of 1.1% per annum according to published forecasts by the National Grid Corporation. In addition, the load shape of different customers was approximated by assigning base, medium and peak demand.

Each customer has a decision rule that formulates the price expectation for the following year, based on current year's price plus some expected change. Based on this price expectation Customers formulate a contract demand curve, for each of the fore-mentioned types of load, expressing price preferences using the tariff price as a benchmark. Customers will always satisfy their demand with electricity contracts at any price below the tariff price, but they will buy no contracts if the price is higher than the tariff price.

Running the electricity markets model

In systems modelling, running the model is not clearly decoupled from model conceptualisation and design. Instead, the modelling team constantly moves between these three stages. As soon as some model results are generated that exhibit 'interesting' behaviour, a new set of questions arise that may require changes in the model structure in order to be investigated. And often they may lead to a re-evaluation of the original system boundaries and the inclusion of new entities in the system.

In the Electricity Markets Model, it took several iterations between the above three stages before the team agreed that a requisite representation of the real electricity market has been achieved. And even at that stage, there was nothing 'final' about the developed model but rather it was felt that the model encapsulated the current state of the mental models of the team members and as these mental models inevitably evolved so would the model.

At the end of the project the resulting model was almost overwhelming in size and level of detail. Inheritance and aggregation helped structure the information in the model and hide complexity. But when it came to running the model the team found that understanding the links between cause and effect was one of the main difficulties. To facilitate the analysis of results, the dynamic communication between the simulation engine of OO/DEVS and spreadsheets was used. Most of the variables of interest were fed to spreadsheets where the financial analysis of the position of the main generating and distribution companies was carried out and a number of different graphs were generated. This helped initially the validation of the model and then the study of the impact of changes in various model parameters.

It should be pointed out that within the spreadsheet each model entity was represented in a different sheet. Fourteen different sheets were used to output variables from the fourteen basic model entities (namely four generators, four suppliers, three consumers, the contract market, the customers contract market and the pool market). The sheer amount of information output to the spreadsheets (which in no way represents the whole information included in the model), presents a good measure of how well information can be structured and represented within OO/DEVS.

A number of scenarios were investigated in order to address some of the questions that motivated the development of the model and were discussed in section 3. Many interesting insights emerged and the team felt that the results were interesting enough to justify a presentation to a number of senior managers including a member of the board of the REC.

Detailed presentation of the developed scenarios and results would violate the confidentiality agreement between the authors and the REC and in any case is beyond the scope of this paper. Instead some indicative results are presented here that give a flavour of the types of analyses that were carried out during this project.

One of the issues addressed was the relationship between the contract market and the pool market. The price differential between the two markets was very high in the first three years of privatisation and this was mainly due to two factors. Firstly, it reflected contractual arrangements prior to privatisation that were meant to secure the successful floatation of both generating and regional electricity companies. Secondly, it was a result of the high degree of risk aversion on the part of regional electricity companies that were afraid of the price volatility in the newly established pool, of which they had no prior experience.

The questions investigated were whether this differential was sustainable and to what extent less risk aversion to pool exposure would affect that differential. Figures 5 and 6 present results from a scenario of high risk aversion modelled by increasing the slope of the demand curve for contracts. Figure 5 shows the average price differential between the contract market and the pool for base, middle and peak load weighted by the volume of contracts sold. Figure 6 presents the pool exposure of all regional electricity companies which is expressed as the ratio of pool purchases over total electricity purchases. Figures 7 and 8 present the same information for a scenario with low risk aversion. A comparison between the two scenarios shows the very significant impact of the risk attitudes of the regional electricity companies. When they became less risk averse the prices in the contract market and the pool converge quickly and stay at relatively low levels. At the same time the amount of electricity purchased from the pool (namely not contracted for) is much higher than in the corresponding scenario of high risk aversion.

Discussion

In the introduction of this paper it was pointed out that the development of OO/DEVS has been motivated on the basis of what we summarised as: model integration, structure, focus, time-representation and reusability. This large-scale modelling exercise within a business environment, adds a great deal of practical insights about the advantages and disadvantages of OO/DEVS in relation to the initial motivation behind its development. The views presented here,

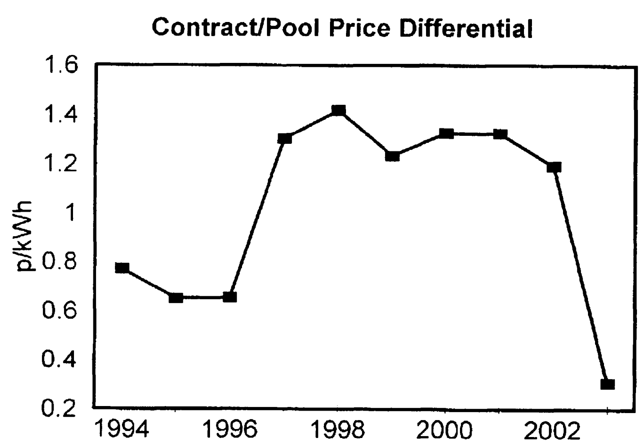

Figure 5 The differential between the contract market and the pool—high risk aversion.

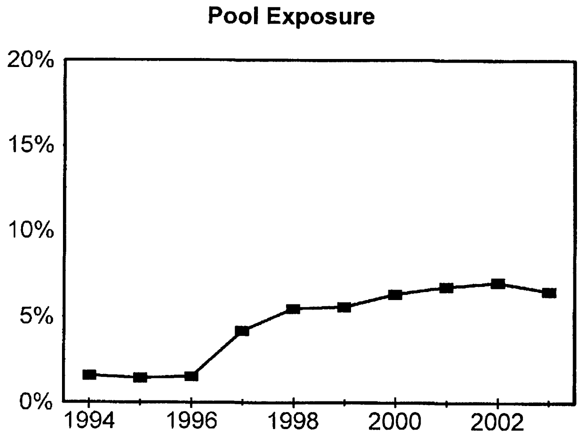

Figure 6 Pool exposure—high risk aversion.

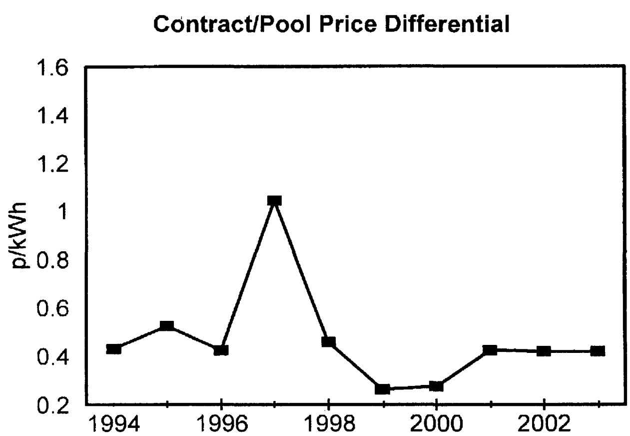

Figure 7 The price differential between the contract market and the pool—low risk aversion.

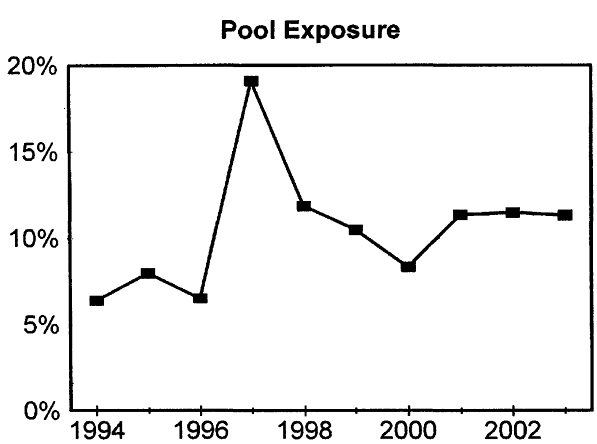

Figure 8 Pool exposure—low risk aversion.

draw from a written evaluation of the OO/DEVS framework and environment, which the REC modelling team contributed at the end of the modelling exercise.

Structure and focus

In terms of structure the concept of the object was considered particularly attractive as: '. . .*building up a model from 'Objects' mirrors the natural world and allows actual characteristics to be modelled*'. In addition, as it has been stated: '*The concept of an 'Object' is very wide ranging, covering both physical entities (for example Generators) and more abstract constructs (for example Curve), yet all can be handled within the same framework*'. The idea of an object as a data container and manipulator, was viewed as a powerful modelling device due to the fact that '*objects can be created to simplify the handling and combination of large amounts of data, essentially in matrix form, extending the scope of the models*'.

Inheritance (namely generalisation relationships) was regarded as a useful tool as: '*New objects can be rapidly created using others as templates, while still retaining all the characteristics of the original*'. Inheritance proved valuable, for instance when it was felt that the model should be extended in order to capture some particular characteristics of the model entities. This was the case with the 'plant bidding decision rule' of Nuclear and Independent Power Producers. While the two entities had all the characteristics of the class *Generator*, their actual behaviour required a slightly different way of modelling. This was achieved by creating two subclasses of the class Generator and overriding one of its methods.

The provision of aggregation relationships was also judged as a useful modelling feature regarding model focus as: '*Objects of the same type can be aggregated together (for example to simulate mergers)*' and '*Models can be built and viewed at different levels of detail/ dissaggregation in particular areas, while still retaining full compatibility* [with the OO/DEVS model as a whole]'.

In addition, the representation of association relationships within OO/DEVS was considered as a feature providing considerable flexibility in designing and building models as: '*Links can be set up between any components in the model, allowing particular interactions to be explored*'. Overall, the use of the decomposition diagram, the level diagram, as well as the object specification forms, were judged as practical tools for conveying information about the system structure. The level diagrams in particular, proved a useful aid in discussing the ways that the model entities influence each other.

Model integration

The potential to integrate OO/DEVS with other models and spreadsheets was viewed as a powerful feature, as in this instance it allowed a mathematical optimisation model, ECAP, whose development preceded OO/DEVS itself, to be integrated within the model. This facilitated the accurate representation of the behaviour (mechanics) of the Electricity Pool in a way that would be impossible to achieve by using for example system dynamics equations. Even in strategic models, the behaviour of certain parts of the system, such as the Electricity Pool, is better represented by 'hard' OR models rather than 'soft' decision rules.

In a similar fashion, the ability to link OO/DEVS to spreadsheet based financial models, facilitated model development, debugging and presentation by giving access to a wide range of tools provided within spreadsheet environments. Overall, OO/DEVS was viewed not only as a modelling and simulation platform, but as a possible integrator of existing corporate models and information.

Time-representation

It was felt that, as the modellers took a year by year view in modelling the Electricity markets, the discrete event view provided by OO/DEVS was useful in modelling the interactions within the industry, as well as features like the coal related contracts and the introduction/retirement of new plants into/from the system. The latter examples are the very instances that are difficult to model naturally within continuous time simulation. Overall, it was commented that: '*The use of messages to trigger methods in receiving objects, allows control over the timing of particular events. It should also make it easier to incorporate processes occurring part-way through a simulation cycle*'.

Reusability

It should be emphasised that the model components (objects) of the 'Electricity Markets Model' were designed with the primary objective that they could be reused. In that respect objects like Curve, Plant, Contract Market and Pool Market were designed and built so that they capture the characteristics of the industry in a generic fashion. The expectation of the modelling team was that the objects of this model would constitute the foundation of a OO/DEVS electricity industry model-base.

In an nutshell, OO/DEVS has proved practical and effective, in a number of areas:

- The natural representation of the model components which proved invaluable in designing the model and communicating its characteristics to the management team.
- The efficient reformulation of the model during the model conceptualization phase by changing either decision rules, message passing between model entities or even the overall structure of the model.
- The smooth transition from a model prototype to more elaborate versions, facilitated by the implementation of the concepts of inheritance and aggregation and the reuse of previously developed model components.
- The exploration of multiple views of the model from different perspectives and aggregation levels using the model decomposition and level diagrams.
- The integration of 'hard' and 'soft' decision rules in the same object, or within different objects in the same model.
- The ability to link the model to spreadsheets, which was particularly useful for model debugging and validation purposes, as the results of the model could be readily used for verification through the use of existing financial models.

Finally, a number of drawbacks of the framework were pointed out by the modelling team. It was commented that OO/DEVS '*still requires familiarity with Smalltalk, which is most readily achieved by users with a programming background. This is particularly apparent in specifying methods and decision rules*'. It was also suggested that the use of some Smalltalk jargon (for example terms like class, instance, etc) could be problematic for the unfamiliar user. In addition to the above, the need for greater auditability and the ability to track through processes and establish why particular results occur, was identified. The considerable size of the model and the bulk of information contained in it, suggested the need for a set of tools for enhanced model browsing and debugging. It should be pointed out that the above drawbacks are mainly related to the current state of the development of the platform and have clearly provided us with useful pointers to a number of future research directions.

Concluding comments

This modelling project was deemed by the client to be successful in a number of ways. First, it allowed the company to address issues that they were not able to address with existing modelling capabilities. In the process, the company carried on using existing pool market and financial models in an integrative fashion within the simulation platform. Therefore, the objective of model integration and reusability were well served. Finally, it went beyond a single-issue model. Easy model re-specification allowed a multitude of related questions to be analysed.

Overall, the simulation platform seemed well suited for model integration of the type required here. In the OR literature, there are several approaches to model integration depending upon the context. For example, from an optimisation perspective, decomposition methods can provide for a hierarchical and modular process of integration, if it seems appropriate that the primary formulation of the problem is one of a mathematical programming. However, since it is policy insight and strategic scenario assessment which is motivating the analytical effort in our case, it was appropriate that strategic simulation should be providing the core methodological focus. Furthermore, given the evolutionary nature of the industry, with its progressive liberalisation, the franchise markets gradually opening up, new generators emerging, not to mention, vertical, horizontal and even diagonal industry re-integration (in the economic sense) through mergers and acquisitions, the need for the modelling platform to provide for easy re-specification of the industry structure was also crucial.

The OO/DEVS approach fulfills this functionality, whilst still maintaining the ability to manage detail at various levels of aggregation. The approach is still a prototype, however, and, as indicated in the previous section, the interface still has some way to go before it can provide the easy modelling interface which has become a characteristic of modern software for system dynamic modelling at a high strategic level. Nevertheless, its success in this application suggests its promise in providing a core methodology for integrative, strategically-focussed modelling support.

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