The Application Of OR Techniques In The Certification Of Software Used To Clear Electricity Markets

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As increasingly sophisticated electricity markets develop, the software used to clear these markets will become more complex. The output of such market clearing programs has financial implications for market participants. It is very important, therefore, that their programs are tested rigorously before certification. The combination of engineering and economic principles used, and the complexity of the formulations underlying these programs, make this task challenging. The authors report on how they have applied OR techniques to certifying the Scheduling, Dispatching, and Pricing software employed in both the New Zealand and Australian electricity markets

I. INTRODUCTION

Around the world electricity is increasingly being provided via competitive wholesale markets. This is the case with electricity in both New Zealand and Australia. The participants in such markets compete with one-another to provide or receive services, with price and quantity bids and offers being the basis for competitive market clearing. While markets of this nature have existed for some time, e.g. in UK and Scandinavia, these markets have generally treated the bid and offer process as a very simply auction, with many of the real world constraints being addressed outside of the market. These can include constraints on transmission power flows, generator operating constraints, and system security constraints. However, addressing many of these constraints outside of the market can reduce the effectiveness of market signals. To reduce the extent of this limitation, New Zealand and Australia have implemented more complex market models which address, to varying degrees, the constraints ignored in older market processes used elsewhere.

The responsibility for satisfying the real world constraints lies with a "dispatcher" who must take bid and offer information, and system constraint information and produce a market clearing dispatch. The goal is to produce a good approximation to an optimal power system dispatch, while determining market prices. To achieve this in New Zealand and Australia, sophisticated Linear Programming (LP) models have been developed to schedule, dispatch, and price both electricity and operating reserves. Such software is described by Alvey *et al.* in [1] The constraints represented within such models typically only approximate the functional form of real world constraints; through they are often very good approximations.

Market software must be tested extensively, as errors can have significant commercial and safety implications. Masiello and Willis [2], in an insightful paper on the implications of electricity markets for software used by system controllers, observed that:

"While (traditional) quality processes often exceed the spirit and letter of `ISO-9000-like' requirements, or even those standards set for software used in the operation of nuclear power plants, we feel they will prove insufficient to fully meet future industry needs because they focus only on assuring that the software's design and manufacture is correct from outside the program and after the fact, and that its performance can be similarly checked."

This certification process becomes complex when the software code is not provided on grounds of commercial sensitivity so that the complied software must be certified as a "black box". This paper explores the use of Operations Research (OR) methodologies employed by the authors in certifying the "black box" market software employed in New Zealand and Australia.

Such certification differs from more conventional software testing in a number of respects. In particular:

- The absence of source code requires that testing be based on comparing inputs, outputs, and the Model specification;
- It was not sufficient to verify the correct dispatch (primal) solution; the pricing (dual) solution has also to be tested;
- The software has significant commercial, engineering, and legal implications for an entire industry. Consequently, testing has to be both thorough and auditable; and

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- A number of features implemented are innovative and not previously tried. This meant that even if the Model is implemented in the intended manner, it is still necessary to identify situations in which it does not behave in the manner intended by those who developed the mathematical formulation.

The testing of these features relies heavily on the application of OR techniques, in designing and analysing tests, as well as reaching conclusions and recommendations based on those tests.

The following section outlines the goals and requirements of this type of software certification. The relevant features of New Zealand and Australian electricity markets are reviewed in Section 3. Section 4 described the process employed in certification and focuses particularly on the role of OR techniques. A discussion of some of the interesting cases and findings encountered during certification are presented in Section 5, with an emphasis on quirks and traps associated with LP formulations and software implementation. Our concluding remarks are presented in Section 6.

II. AN INTRODUCTION TO CERTIFICATION

A. *The Goals of Certification*

Market model software certification entails establishing that the model has been appropriately coded and is fit for purpose. In practice, this amounts to establishing that:

- The market model software (The Model) correctly implements the mathematical formulation specification (The Formulation) as defined, or referred to, by the market rules (The Rules);
- The Model's dispatch solutions are feasible (infeasible) when they should be feasible (infeasible);
- The Model's dispatch solutions are economically consistent, fair, and practicable to the extent specified by the Rules;
- The Model's pricing solutions are as required by the Rules; and
- The Model is very robust and is capable of being used in real time operation.

In some instances, aspects of the Rules may be vague or unclear, allowing some freedom of interpretation of the Formulation to be implemented which may have some implications for fairness and practicality. As an example, Clause 3.8.18 of the Australian market rules [3] requires that:

"If there are scheduled generating units or scheduled loads for which the prices submitted in dispatch bids or dispatch offers for a particular trading interval result in identical prices at a regional reference node then the MW quantities specified in the relevant price bands for those dispatch bids or dispatch offers must be dispatched as far as is practicable on a pro-rate basis."

There are certainly different ways of interpreting and implementing this condition. Possible implementations include a single pass solve with one of a number of possible different constraint forms, some form of interactive re-processing, or simply ignoring the condition. Each option may have implication with respect to other parts of the Rules, both with respect to dispatch and with respect to pricing.

In these instances, scope must exist in the certification process to provide feedback to the client on the performance and implication of a given Formulation procedure. Given this information, the client may choose to alter the Formulation or direct that a particular implementation be adopted.

When features of the software fail this certification process the software must be revised and retested.

B. *The Skills Required for Certification*

A project of this nature requires skills in a wide range of areas. The three basic skills are optimisation theory, power system operation, and power system economics.

A thorough understanding of optimisation theory is required so as to interpret the Formulation so as to design meaningful and comprehensive software tests, as well as to manually verify the results and to interpret unexpected Model behaviour. It is particularly important to understand the primal/dual relationship, as the Model's response to specific (dual) pricing scenarios can only be tested by engineering the corresponding dispatch (primal) event. Many tests involve manually reconstructing market prices from reported, or derived constraint shadow prices and from the marginal impact that each relevant primal variable has on a constraint.

An understanding of optimisation theory alone is not enough though. It is also essential to understand the system – both physical and economic – which the Model is intended to represent. An understanding of power system operation is required so as to be able to quickly develop a scenario which will elicit the desired Model response. An understanding of how power systems work in reality is also required to establish that the Model is "fit for purpose", and, in particular, that solutions given by the Model will not have hitherto unforeseen, and unacceptable, implications for the market dispatch.

Similarly, an understanding of power system economics assists in designing pricing tests. It also assists in identifying situations in which Model/Formulation price outcomes may be inconsistent with the rules, or with economic theory.

III. THE NEW ZEALAND AND AUSTRALIAN MARKETS

The market models, and the general environment, in New Zealand and Australia in their electricity markets differ somewhat. This section provides a summary of the relevant features of these markets.

A. *New Zealand*

The New Zealand wholesale electricity market started on October 1, 1997. The Formulation implemented in the scheduling, pricing and dispatch software (SPD) was defined by Transpower New Zealand Limited [4] based on the requirements of the New Zealand Electricity Market Code [5].

Given generator offers, and either demand side bids or load data the market model [1] uses transmission lines modelled and with power flows governed by a relatively accurate linear "direct current" (DC) approximation of the "alternating current" (AC) reality as demonstrated by Ring *et al* [6]. That is, the power flow obeys Kirchoff's Law of power flow, rather than that of a transportation model. Transmission losses, which increase quadratically with line flow in reality, are modelled using a piece-wise linear approximation of the loss function for each transmission line. Other constraints include:

- Flow capacities of transmission lines, approximately the conductor heating limits on lines;
- Ramping constraints on generators which limit the rate of increase or decrease in generation; and
- Reserve constraints, which require that sufficient surplus generation capacity or "interruptible load" be available within a few seconds so as to cover the failure of the largest contingent event (ie. Generator or transmission line failure in each island.

The objective function maximises the differences between the value to the market of all demand side bids cleared and the cost to the market of all energy and reserve offers by generators, an, in the case of reserve offers, interruptible load. Additional terms are included to allow the violation of constraints at high penalty costs so as to give an indication of factors preventing a feasible (unpenalised) solution from being determined.

The Model is used to:

- Schedule the system, whereby up to 30 hours prior to the dispatch period all generators and loads are scheduled for dispatch based on their bids and offers;
- Dispatch the system in (approximately) real time, whereby generators are dispatched based on their bids so as to meet the forecast load; and
- Price, whereby generators are notionally dispatched after the event so as to meet the actual load that was met, with the LP shadow prices being used to define the market prices.

Some interesting features of the New Zealand Formulation are:

- A very large number of nodes are modelled relative to other markets. Over 150 injection or off-take prices are represented, with energy prices determined for each in each half-hour.
- The detailed representation of electrical reality means that power flows and prices behave in a manner which may not be immediately intuitive to those who are not familiar with the physics or such systems. In particular, prices throughout the network may be very sensitive to transmission constraints. Prices can even be forced negative, which gives rise to non-convexity problems.
- The reserve constraints serve to make the reserve and energy prices functionally dependent.

B. *Australia*

The certified Model was first used in Queensland in January 1998 with a national market version, covering the eastern states from Queensland to South Australia being used in the National Electricity market in December 1998. Unlike New Zealand, the market rules, which are embodied in the National Electricity Market Code [3] are enacted by an act of the Federal Government. The code does not specify a formulation, but imposes conditions on the formulation. The market operator, NEMMCO, has interpreted these conditions and worked with the software provider and the industry to develop an appropriate formulation.

The market Model aggregates regions as a single regional reference node. The regions generally correspond to states, though the Snowy Hydro region is treated as a distinct region while the Australian Capital Territory (ACT) is merged with New South Wales. Bids and offer prices at market nodes (these being physical generator and load connection points within a region), are adjusted by fixed loss factors to give an effective loss adjusted bid or offer price at the reference node. A linear transmission system is currently employed between regions, with no loops being formed. This means that a transportation model is sufficient to capture the physics of the assumed system. Transmission losses are again modelled as piece-wise linear approximations, but represent only the losses on the physical interconnection between regions, not those on all the lines notionally combined into the modelled interconnector. Loads are generally modelled as being fixed, though some dispatchable load is represented. Other constraints include:

- Ramping constraints on generators which limit the rate of increase or decrease in generation relative to the previous dispatch period
- Tie-breaking constraints which require that equal price bids and (separately) equal priced offers in a region be cleared in a pro-rated fashion;
- Generic constraints which allow any linear combination of regional generation, generation less dispatchable load at each modelled market node, and interconnector flow to be constrained as required. These constraints are used to represent otherwise unrepresented constraints both within regions and between regions;

- Energy constraints on fuel availability; and
- Logic to start-up and shut-down generators which can come on line during a dispatch period.

The objective function maximises the difference between the cost of all demand side bids cleared and the cost of all energy offered by generators. Again, additional terms are included to allow constraint violations at some penalty cost.

A complex set of reserve constraints, covering six classes of reserve, are co-optimised with the energy constraints.

The Model is used to:

- Schedule the system, whereby several hours prior to the dispatch period all generators and dispatchable loads are scheduled for dispatch based on their bids and offers given forecast load;
- Dispatch the system each half hour, whereby generators and dispatchable loads are dispatched based on their bids so as to meet forecast load; and
- Dispatch the system and price each 5 minutes, whereby generators and dispatchable loads are dispatched based on their bids so as to meet current load levels. Market prices are based on LP shadow prices. The five minute prices are combined to form an average half hourly price.

Some interesting features of the Australian Formulation are:

- The low level of detail of the system means that the modelling of interconnector flows is more complicated than in New Zealand, with interconnector parameters being updated outside the Model each half hour so as to account for the changing nature of the real transmission system.
- Many generating units may wish to stay on overnight as this is cheaper than switching them off. This requires negative priced offers which can cause market prices to go negative, and may give rise to non-convexity problems.

IV. CERTIFICATION PROCESS

A. *Test Systems*

The first certification under-taken was for the New Zealand system. As this system comprises over 150 connection points it was not deemed practical to work with a representation of the full system. Instead, a number of smaller systems were used, comprising 8 – 10 nodes. The systems were designed so as to include key features of the real system, including transmission loops, interconnections between the two islands, and a more or less accurate representation of key generation plant. This system was simple enough that the full solution for the energy dispatch could be presented on a one page map of the system, with additional reserve dispatch details being presented on a separate sheet. This significantly simplified analysis and interpretation. An example of such a sheet used for New Zealand is shown in Figure 1.

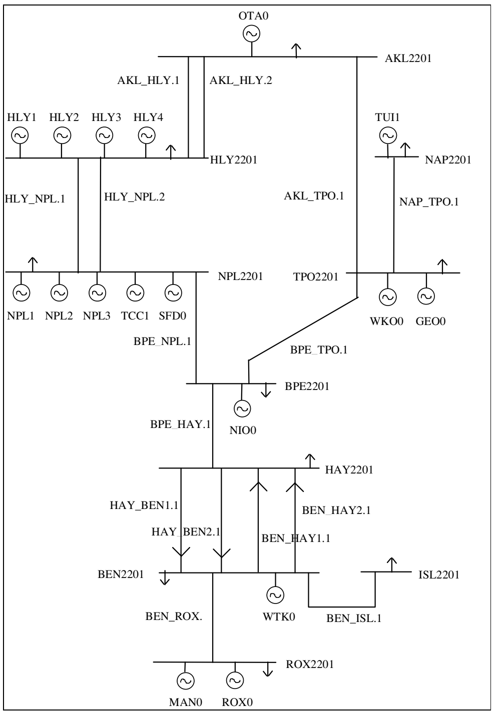

Figure 1: New Zealand Test System

The situation for the Australian certification was different due to the smaller system represented. At the time the certification process began, the proposal was for a 3 node system in Queensland, and latter a 4 or 5 node system for the national market. We choose, therefore, to use a 4 node system for testing purposes, with a reduced number of generators and loads in each region. Subsequently, a single region market was adopted in Queensland.

B. *The Certification Methodology*

The basic certification methodology involved establishing that all aspects of a simple case, with no constraints imposed other than the most basic electrical constraints, were correct, and then perturbing this case so as to test other features.

This "base case" would be tested very extensively. Some examples of the tests which might be conducted include:

- Manually calculating all branch flows and losses given injections and off-takes;
- Manually calculating all prices given the injections and off-takes to determine the cost of meeting an infinitesimal change in demand. This is essentially an application of duality theory; and
- Checking that, at each node, no bid (offer) is cleared which has a price less than (greater than) the local market prices, while all bids (offers) with prices greater than (less than) the market price clear. This is a very basic but effective optimality test.

Superficially, the testing process for other features is quite simple. Having accepted the base case solution, the imposition of a simple charge in the data, or the inclusion of a new constraint should change the base case in a manner predictable from the Formulation. The situation in practice may be somewhat more complicated. First, while a model feature might be said to be “tested” by doing a single test which is consistent with the Formulation, the test itself may not be comprehensive. Typically a large range of tests must be designed to test a single feature, with these tests being carefully designed to test a particular facet. A simple example is the testing of the bounds on the flow on a transmission line. It is not sufficient to simply show that if the bound is tight enough, it will constrain the line. A more appropriate set of tests need to show that:

- The dispatch is correct given a binding flow constraint;
- The prices are correct given a binding flow constraint;
- The line is not constrained when the flow limit is set at a level in excess of the optimal unconstrained flow level, and that the corresponding constraint shadow price is zero in this circumstance;
- If the flow constraint is set equal to the optimal flow then the shadow price should also be zero;
- If the upper flow bound is below the lower flow bound then the problem is infeasible;
- If some other constraint is imposed which holds the flow at the same point implied by the flow constraint then an appropriate pricing result occurs, given that only one constraint need have a non-zero shadow price; and, finally,
- The constraint shadow prices have the correct values.

If a model feature passes a wide variety of tests of the nature then this may be taken to indicate that the Model is performing appropriately. However, care must be taken when a Model appears to fail a test. It is quite possible that the expected outcome is not the correct outcome. Expectations biased by preconceptions based on how power systems have been operated, or by the stated intentions of the industry in proposing a Formulation, may not be appropriate given the Formulation actually implemented. Thus, while the Model may appropriately reproduce the Formulation, the behaviour of the Formulation may be at variance to what the market expects, or even from what one might expect by reading the Formulation.

Thus, when a Model feature appears to fail a test, it is necessary to ascertain what the Model is actually doing. Further tests may indicate a misplaced parenthesis, or a reversed sign, but they may also demonstrate consistent with the Formulation. Some such features can require a very significant amount of investigation. For instance, in the New Zealand Model a situation can occur in rare situations whereby prices fall in the direction of power flow without any transmission constraints binding. While this appears counter intuitive based on the assumptions of simple tests, such effects have since been shown to be an artefact of the piece-wise linear loss representation used.

Similarly a result which is in line with the expectation is also checked as shown above to ensure that it is indeed correct.

The table below summarises the key features of the certification process.

	Expectation of model behaviour correct	**Expectation of model behaviour incorrect**
Model feature appeared to work	Model feature passed	Undetected problem with the Model
Model feature appeared not to work	Model feature failed	Do further tests to understand Model, re-assess Formulation

C. Re-testing

If features in the Model change, whether due to the correction of problems found during earlier certification or to changes made to the Formulation, the Model must be re-tested.

Given a collection of previously tested cases, it is generally relatively straight forward to re-run these to check the modified software. Additional tests which relate specifically to the new version can be conducted using the standard methodology.

D. Advantages

This approach to certification provides a more solid audit trail, in the form of saved solutions and written up cases, than simply reading the source code of the program. Further, many cross-checks occur implicitly within the tests. In particular, duality results verify the primal results. For example, if the price at one end of the power system is correct when calculated relative to the price at the other end, then this implies that all constraints which should be driving those prices are also behaving correctly.

Another significant advantage of this approach is that it is possible to identify practical flaws in the Formulation which might be overlooked if copies of the Formulation and source code were simply compared. This allows the client to be informed of unexpected model behaviour before the software goes “live”, allowing time for the industry to be informed of the prospective result, and/or the issue to be removed by changing the Formulation.

E. Limitations

Although the “black box” certification approach can be very thorough, it cannot guarantee that problems do not exist in the source code. Indeed, all that can be stated with certainty is that a given feature performs accurately for some tests, and definitely failed other tests. The possibility always remains that an undocumented feature has been implemented, the effects of which is only observable under very special conditions. This is not to say that such features can never be found. For example, during the testing of the

New Zealand Model an extreme test of the “spring washer” pricing effect (see [6] and [7] for a description of this effect) produced unexplainable results which were eventually traced by the software provider to an undocumented constraint on voltage angle differences across lines.

Finally, this form of certification can be relatively expensive and time consuming.

V. EXAMPLES OF PROBLEMS FOUND

Problems can be classified as implementation errors, formulation problems, and problems related to the real world implementation of the Formulation/Model.

Implementation errors found have included:

- Misplaced parentheses in constraints;
- Undocumented constraints in the software, some of which were not be required by the Formulation;
- Division by zero errors; and
- The addition of surplus primal constraints was counter productive for pricing purposes, as situations would occur where more than one constraint imposed the same bound, with only one of these having a shadow price. While the resulting energy prices might be unchanged, the reported shadow prices can be difficult to interpret and may lead to confusion.

Removal of a circuit which forms a part of a transmission loop will result in the loop being broken into a two spurs with prices which increase along the spur. However, while simply setting the flow constraint on the circuit concerned to 0 MW will achieve the same primal (power flow) result, it will result in a pronounced “spring washer” pricing effect across the constrained line and around the entire loop. The certification process has highlighted the fact that lines were being constrained to zero flow when they should have been removed from the Model The Model was changed so as to eliminate such lines from the electrical representation within the Model.

The most significant Formulation problem found relates to non-convexities. In the New Zealand certification tests were conducted to ensure that the Model could produce negative prices when transmission constraints were imposed in transmission loops. Such negative prices should stem from the so called “spring washer effect”, which results in prices being forced up on one side of a transmission constraint in a loop, and down on the other, potentially to levels below zero.

Negative prices were achieved in the New Zealand Model, but the transmission losses and line flows were shown to be incorrect. Further investigation revealed that the negative prices had encouraged the Model to maximise losses, rather than minimise losses, with the result that the highest loss segments of the piece-wise linear loss function were being used before the low loss segments while flows were being sent in both the forward and reverse directions simultaneously so as to further amplify losses. That is, the negative prices created non-convexities in the Model. This was not a problem with the Model per se, but reflected a feature of the Formulation. The New Zealand market is aware of this limitation, but to date it has been accepted as negative prices have rarely been encountered in a pricing solution run.

A similar phenomenon occurs in the Australian Model where negative market clearing prices arise due to negative generator offer prices and the Formulation contains an approach to deal with the resulting non-convexities.

Problems found which relate to the world outside the Model include:

- Discrepancies between definitions of data provided by external data sources and use of the data within model; and
- Conflicting constraints being established, such a one constraint requiring generation at a source to be greater than 100 MW (for example) while another constraint requires the same generation to be less than 50 MW.

VI. CONCLUSION

The testing process conducted in certifying this software may not be of itself a new application of OR. Models developed for major roles in industry are presumably carefully checked and tested by those who use them. However, these tests may only relate to the primal solutions, with the dual being discarded. Further, the testing process may be “in house” allowing some scope for acceptance of formulation and testing errors. In particular, even when the testing process is inadequate, the results may not be challenged. Finally, the source code will often be available to the testers, suggesting that a check of the source code is sufficient.

The certification undertaken for the Australian and New Zealand electricity markets differs in that the software has significant commercial, engineering and legal implications for an entire industry. Furthermore, cutting edge technology has been employed, both in the Formulation and implementation, which is largely untested in practice. This has required a very detailed testing of the software functionality and fitness of purpose to be conducted, and detailed documentation to be provided.

A particularly unusual feature of this certification was that the market had stated a Formulation, the supplier had stated which equations were implemented, but the testers were not privy to the source code. Consequently, a “black box” audit was required. While this is time consuming, and cannot guarantee the correct operation of the software in every conceivable situation, it has proven to be a robust and thorough means of testing. Unlike many other testing processes, it was necessary to test both Primal and Dual solutions simultaneously; it was not good enough to have a correct dispatch if prices were inconsistent.

The testing requirements of future electricity market models may be even more demanding than those discussed here. Future models may represent the full AC representation of a power system, with complex trigonometric relationships and strong interdependencies between variables. While the same principles as discussed here would apply, the complexity of testing would be greatly increased.

VII. DISCLAIMER

This paper reflects work conducted by PHB Hagler Bailly – Asia Pacific Limited (now PA Consulting Group Asia Pacific Ltd) for Transpower New Zealand Limited and for the (Australian) National Electricity Market Management Company. However, the contents of this paper solely reflect the personal views and opinions of the authors.

VIII. REFERENCES

[1] T.Alvey, D.Goodwin, X.Ma, D. Streiffert and D.Sun, "A Security-Constrained Bid Clearing System for the New Zealand Wholesale Electricity Market", IEEE Trans

[2] R. Masiello and L. Willis, "ISO-Raising the Bar for Power System Software". The Electricity Journal, November 1996, pages 18-25 "National Electricity Code", Draft version 2, 24 September 1996. Available at http://www.neca.com.au/code/.

[3] "Scheduling, Pricing and Dispatch Software: A Mathematical Description", Transpower New Zealand Limited, September 1996.

[4] "Rules of the New Zealand Electricity Market", The Electricity Market Company, Wellington, New Zealand, 1996.

[5] B. J. Ring and E. G. Read "A Dispatch Based Pricing Model for the New Zealand Electricity Market", in M. Einhorn and R. Siddiqi (Editors), Electricity Transmission Pricing and Technology, Kluwer Academic Publishers, 1996.

[6] E. G. Read and B. J. Ring "Dispatch Based Pricing: Theory and Applications" in A. J. Turner (Editor) "Dispatch Based Pricing", Transpower New Zealand Limited, 1995.