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Autor(en): **Smeers, Y.**

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The Analysis of the Energy Supply in the Belgian R&D Energy Program

by Y. Smeers, Louvain

Optimisierungsmodelle für Energieflüsse werden seit langem verwendet, um Energieproduktionssysteme darzustellen und abzuschätzen. Heute sind diese Modelle sehr ausgeklügelt, ohne dass man aber auf die Energiebedarfsprobleme zu sprechen kommt. Die Detaillierung eines globalen Modells hat nicht immer eine Qualitätsverbesserung des Modelles und seiner Resultate zur Folge. Um dies zu vermeiden, erlauben sehr detaillierte Modelle, die hierarchisch klassiert und mit zusätzlichen Daten verknüpft verbunden sind, genaue Spezifikationen zu erhalten (Energiesparung, Fernwärme . . .). Dies ist wesentlich für Länder ohne eigene Bodenschätze. Da die Verbindungen zwischen den hierarchischen Modellen nicht einfach zu bestimmen sind, beschreibt der Verfasser einige dieser sehr detaillierten Teilmodelle, die in einem ersten Zeitabschnitt im globalen Energieproduktionsmodell enthalten sind.

Les modèles d'optimisation des flux d'énergie sont depuis longtemps utilisés pour représenter et évaluer les systèmes de production d'énergie. A l'heure actuelle, ces modèles deviennent de plus en plus sophistiqués, sans même que les problèmes de la demande d'énergie soient abordés. Le niveau de détail croissant dans un modèle global n'implique pas toujours une augmentation de la qualité du modèle et de ses résultats. Pour éviter cela, des modèles très détaillés, classés de manière hiérarchique et reliéspar des valeurs agrégées permettent de garder des spécifités très importantes (économies d'énergie, chauffage à distance . . .), surtout pour des pays sans grandes ressources indigènes. L'auteur décrit quelques sous-modèles très détaillés qui seront, dans un premier temps, incorporés dans le modèle global de production d'énergie, les liens entre modèles hiérarchiques étant difficiles à trouver.

Energy flow optimization models have been extensively developed in the last few years. These models originated in the classical activity models constructed in the fifties for electricity generation and refinery processing; they currently include most of the energy supply and demand sectors (at least industrial demand sectors). In the energy research and development program sponsored by the Belgian Department for Scientific Policy, energy supply and demand have been separated in two different models that will eventually be integrated. The work on energy demand is discussed in other parts of these proceedings. In this paper we discuss the modeling activity for the supply sector.

As just mentioned *global energy flow models* have already been developed in several places: well known examples are the different Brookhaven models (BESOM, DESOM, RESOM, . . .) [4, 7, 11], and the supply model of the Project Independence. In *Europe*, models of this type have been developed in *KFA in Jülich, IEJE in Grenoble* and the *DG XII at the Commission of the European Community*. The latter is currently being implemented in each of the nine countries. In a similar context, the IEA has also developed an energy flow optimization model of the LP type [12]. Finally and just to say a word about the problem of integrating different models, let us mention the PILOT model developed by *G. Dantzig* and his group in *Stanford* (a similar model being constructed at the *Technion* in *Haifa)* which presents an example of integration between a simple energy flow model and an I/O based macroeconomic model [5].

A characteristic of several of these modelling efforts is the *continuing evolution towards more complex models leading to a more realistic representation of the different activity processes*. Indeed the level of complexity adopted in existing models is very often determined by the limitations resulting from the manipulation of large amounts of data both in the generation of the model (maintenance of the data base) and in its optimization (multiphase models, regional models, . . .). Consequently the current level of detail in the representation of the energy processes is very often arbitrary and is not the result of a careful evaluation of the quality of the model.

This way of choosing a level of representation in the models is probably inadequate for Belgium. Indeed like most European countries our dependence on imported oil is extreme and only small savings on imported primary energy can be hoped for; moreover preliminary studies seem to indicate that non negligible savings can only result from the *combined development of several energy conservation activities*. It is thus a requirement for an energy flow optimization model to be able to forecast with good accuracy the (rather small) share of energy consumption that can be captured in the future by the different conservation processes. To illustrate this point, let us consider the demand for house heating: this demand represents 25.6% of the total primary energy consumed in this country [6]. Because of our mild temperature, district heating which is considered to be a promising field for energy saving in this area can be expected to achieve 7% of this demand (with a sufficient rate of return (5%) on investment) [6]. Similarly, the few sunny days Belgium enjoys do not make the development of solar energy extremely promising. As a consequence, energy savings in this country can only be the result of a diversified portfolio of energy conservation activities, the development of which has to be studied with the highest care. Particularly, it can be expected that simplified LP models would exhibit too much «bang bang» effect for their conclusions to be implementable.

Two alternative paths for research thus remain available: one can try to develop elaborate LP models based on very detailed representations of all activities or rely on a hierarchy of models, the models in one level giving a detailed representation of entities used at the level above. It is always easy to call on hierarchical systems when the situation becomes complex, it is more difficult to identify exactly the different links between the parts of these systems. The kind of hierarchical system that we here have in mind (but that we are not presently pursuing in our research project) is exemplified by the capacity expansion models for electricity generation developed at Electricité de France [3]. In this work, the top level model which has to decide of the different investment variables has a nonlinear objective function consisting of a linear part depending on investment variables and a nonlinear part representing the sum of operating costs for each period. The latter is in fact computed at each iteration by a more detailed models, optimizing the operation of the equipment for each period. Thanks to these short term models one can realistically take into account phenomena that can hardly be represented in a single LP model such as forced outages, random demand, maintenance planning, reservoir management, spinning reserve requirements, ...

In principle, this *hierarchical approach* is more satisfactory than the construction of a single global model. It thus should be extended to multisectorial models for representing those sectors that interact with the power system such as district heating, solar energy, ... This approach though potentially more powerful, departs too much from the current status of global models to be attempted with enough guarantee of success; if it were to be pursued, short term operations models for interwoven sectors should be developed in order to calculate the operating cost in the global investment model: the investment model would be a large nonlinear model (whether cast in the optimal control framework as in the Electricité de France's models or not) with as many variables as the number of equipment types multiplied by the number of periods. Codes for such problems are by far not as readily available as for linear programming. Moreover, it can be mentioned that this hierarchical approach naturally leads to *nondifferentiable functions:* more specifically the operating cost during one period is a nondifferentiable function of the existing capacities (although this problem didn't lead to difficulties in the Electricité de France's work model so far).

For the time being, the LP approach is certainly the most widely used and it is also the one presently pursued in the Belgian R&D project. In order to adequately select to what extent this future global model should be detailed, the research effort has been mainly put on sectorial models which we try to design with all the required detail compatible with the LP representation.

Capacity expansion for electricity generation

The first constructed model deals with capacity expansion for electricity generation. As discussed in the introduction, this type of model is now classical at least in its deterministic version discussed in this section. An effort has been made to obtain a rather detailed LP model which could be used later as a benchmark for choosing a suitable representation to be included into the global model. We shall not elaborate here on the basic elements of capacity expansion models, for electricity generation, the reader is refered to [1] for a discussion on this subject. On that ground, we can describe the model by giving the following characteristics:

- the user is free to specify as many daily load curves he wishes;
- for each daily load curve, two types of storage can be included (weekly cycle is not assumed);
- continuous maintenance variables have been included. They occur in constraints expressing the total number of hours of availability for each equipment. The model has to allocate these hours of operation during the year. Theoretically, this formulation does not guarantee a feasible maintenance schedule (which can only be represented by using integer variables). Though in practice experience has shown that the results are perfectly adequate as a first approach to maintenance planning.
- in order to reduce the size of the problem Z-substitutes are included for all (production and pumping) operations variable in a daily load curve.

The model is constructed by a special purpose matrix generator written in PL 1, the output of MPSX is immediately read by a program which computes the «Loss of Load Probability» in each of the planning periods. The treatment of forced outages is classical in the sense that a reserve coefficient is chosen so as to reach an adequate number of shortage hours (10 hours/year). It was not attempted to define a shortage cost nor a set of forced outages configurations, that would have made it possible to replace the operating cost by an expected overall operating and shortage cost. This approach, though quite sensible from an economic point of view cannot be carried through as such to global models because of the size of the LP that it implies. The selected approach consists in revising the reserve rate based on the results of the LOLP. Though very common, this procedure has some drawbacks, in particular the capacities are replaced by derated capacities in the computation of operating costs (in our case taking only into account forced outages) which leads to a slight underestimation of the operating costs. Moreover, the optimization requires a two step procedure since it is necessary to correct the results of the LP using the LOLP. It seems difficult to improve upon this situation without relying on hierarchical models: a theoretically sound approach to the problem would require the use of expected operating cost and not an underevaluation based on derated capacities. Moreover, reliability constraints expressing that a maximum of 10 hours of shortage per year are allowed should be directly included into the program. Unfortunately, these two requirements are difficult to achieve in practice in a single model:

- the computation of expected operating cost is based on the LOLP curve ([1, 14]); it is thus rather costly to perform and impossible to implement in a linear programming framework;
- reliability constraints can be directly introduced in investment planning models using their deterministic equivalents. However, different attempts to obtain adequate probability distributions for the Belgian case have failed. The relatively small number of nuclear plants and large classical units in the distribution of available capacity is probably responsible for that failure.

An important question can be raised as far as the opportunity of including pumping storage in a capacity expansion model is concerned: indeed detailed studies [13] have shown that their role in energy transfer (which is the only one taken into account in LP investment planning models) is by far not the most important: it seems that in the future, pumping storage will be used mainly for reliability purposes or for easing the dispatching of the different plants.

In that case, it is not obvious that the additional complexity pumping storage introduces in the optimization process is really worth the increased realism brought about by the representation of energy transfer. Additional studies are needed to clarify this problem.

Stochastic model for electricity generation expansion planning

The purpose of the deterministic model recalled in the preceding section is to determine the optimal decisions that have to be taken now once the evolution of the different exogenous variables of the system (demand, cost, equipment availability, ...) is given. It is clear that the future value of many of these parameters is by nature unknown and that the decision maker will only acquire additional information about these parameters as time goes on.

The problem of finding an optimal decision process tackling directly this uncertainty can be formalized using event trees. Event trees have been known for a long time in Decision Sciences and have recently been popularized in energetics thanks to the *Rasmussen study;* for a detailed treatment the reader is referred to any classical source on the subject [10]. Different approaches exist among which we shall only mention two. We first introduce some notation: let *i* be a node in the event tree where *i* represents «a state of the world» (which can be roughly defined as all the information collected about the system by the decision maker up to *i*). A path P_{oi} from the origin to *i* is a scenario; let I_T be the set of states of the world that can be reached in period *T*, I_T will then designate the set of terminal nodes of the event tree, the set of scenarios considered in the problems is thus:

$$[P_{0l}; l \in I_T].$$

If we let x_i be the investment decision made at *i* and if the current level of equipment at node *i* is defined by Z_i, we have (assuming no dismantling):

$$Z_i = Z_0 + \sum_{j \in P_{0i}} x_j.$$

If $\psi_i (Z_i)$ denotes the operating cost at node *i*, the deterministic model for a scenario P_{ol} can be written as:

Seek

$$C_{ll} = \text{Min} \sum_{i \in P_{0l}} [K_i x_i + \psi_i (Z_i)],$$

$$\text{s. t.} \quad Z_i = Z_0 + \sum_{j \in P_{0i}} x_j, i \in P_{0l},$$

where K_i is the vector of investment cost at node *i*.
Let (x^1, Z^1) be the decision variables (investment and operating cost) obtained in scenario 1, and let C_{1l}, be the cost under scenario 1' of (x^1, Z^1). The decision criterion is then:

$$\min_{1} \max_{1'} (C_{ll'} - C_{ll}),$$

which implies choosing the strategy that minimizes the loss occuring if the assumptions corresponding to that strategy do not materialize. This is obviously a very cautious attitude.
A different approach which has not yet been extensively experimented is suggested by economic theory. It consists in dealing immediately with the whole set of possible evolutions and not only with a single scenario. The problem can then be written as:

$$\text{Min} \sum_{t=1}^{T} \alpha^t \sum_{i \in I_t} \prod_{(k,l) \in P_{0i}} p_{kl}$$

$$[K_i x_i + \psi_i (Z_i)]$$

$$\text{s. t.} \quad Z_i = Z_0 + \sum_{j \in P_{0i}} x_j, i \in T,$$

where $\prod_{(k,l) \in P_{0i}} p_{kl}$ is the probability of the occurence of node *i* in the event tree.

The reader will here easily recognize the deterministic equivalent of a problem with recourse based on the event tree.
In order to be able to systematically investigate whether this approach (which is theoretically more adequate) really brings additional insight into the problem of constructing strategies, the matrix generator of the deterministic model has been extended in order to accommodate such problems. The size of the linear program clearly rises rapidly with *I*; possible ways of overcoming this difficulty are currently investigated by using the procedures discussed in section «Large Scale Optimization».

Submodels being currently developed

Different submodels are currently developed or looked at in order to proceed towards a global supply model. At this stage the nuclear fuel cycle has been developed and a model for combined production of heat and electricity will soon become available; a general framework for studying distribution phenomena has been established as well. The fuel cycle model considers several types of nuclear reactors and the production of the corresponding fuel. Its writing is rather straight forward and we shall not elaborate on it here. The next section will instead be mainly devoted to combined production of heat and electricity which involves complex subannual flows.

Combined production of heat and electricity

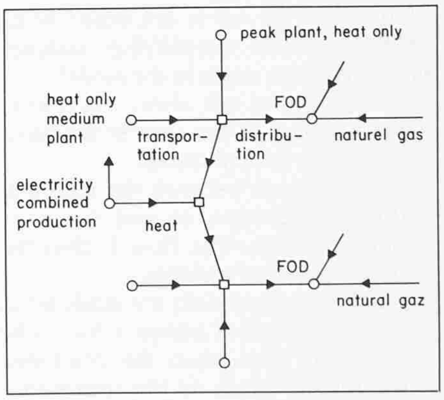
The modeling of combined production in a global framework is constrained by the following contradictory requirements:

- the model should be sufficiently refined to be valid;
- this refinement rapidly generates a very large number of constraints.

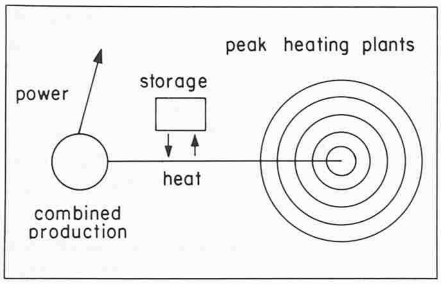
Before presenting the model being currently developed, we briefly discuss these two points:
1) The development of combined production for district heating is thought to be one of the different energy conservation processes able to bring a significant (but still limited) reduction of our primary energy imports. In particular, the profitableness of such projects will depend on:

- the location of the combined production (distance to the demand),
- the density of the demand,
- the marginal cost of electricity during the year.

This dependence requires in the global model a desaggregation of the demand for heat into its temporal (in order to take into account the nonsimultaneity of the loads) and spatial components. In particular a load diagram should be given for the different urban districts of the nation. (The relevant data have been collected in another group of the Belgian R&D research program and are available.) This disaggregation immediately leads to the second point.
2) Let *T* be the number of periods considered, *n* the number of different urban districts in the nation and *K* the number of different demands in a period. The number of constraints to express the satisfaction of the demand is of the order *KnT*. Moreover, because the load curves for heat and electricity behave rather differently and do not reach their peak at the same time, *Z* substitutes can no longer be used to reduce the number of constraints relating the capacity and the operating variables. As a consequence, the number of constraints rapidly becomes prohibitive.
With these two requirements and given that one wants to remain in the LP framework, the most natural approach consists in developing two types of models that are intended to interact, the nature of this interaction being rather unformalized. We briefly discuss these two models.
The combined production submodel considers different demand nodes, each of these nodes being fed with different sources of heat namely FOD, natural gas, local heat plants, and combined production plants. Specific transportation and distribution costs are associated to each node (fig. 1). These costs are computed using models developed in other groups of the Belgian national R&D program.



There are several means to write the demand constraints at each node depending on the margin of freedom that one wants to leave in the optimization. Since more freedom also means more constraints and variables, the final choice of the margin of detail of the representation will be made when enough information about the operation of the plants has been collected using separate detailed models of district heating. It is the goal of the model described below to provide this information: it refines the scheme used in the global combined production model by considering several different zones of demand for urban heating and by using an accurate representation of the load curve in each zone. The actual version of the model is static but it is currently being extended to make it dynamic. The goal is to identify the general behaviour of the penetration of district heating and to provide simplifications that will be imposed on the operations variables in the global model. It uses as input the marginal value of electricity during the different periods of the horizon. Its general principle can be described as follows. Let us assume, for simplicity that the demand node can be connected to only one combined production plant and that the demand node is decomposed into several districts corresponding to different geographical characteristics for which the load diagram is given.



The aim of the model is to determine:

- which districts should be connected to the district heating system,
- which combination of plants should be installed,

so as to minimize the overall cost for satisfying the demand for heat in the system.

A special matrix generator has been written and the LP is optimized using MPSX. Several simplifying assumptions have been made in the model:

- electric power can always be sent to the network at the current marginal cost of the central system;
- the difference between the temperature of the water to and from the plant is given. The flow is thus the only regulation variable;
- reliability constraints are modeled as follows: installed capacity has to be sufficient even when the combined production plant or the transportation network is down: these events are assumed to occur with a certain probability and the model should minimize the expected cost taking the contribution to overall cost entailed by these events into account (this is the classical approach adopted in the Electricité de France models).

Large scale optimization*

Energy flow optimization problems are usually very large and more refinement will increase their size. Moreover, when certain phenomena are explicitly modeled (reliability constraints, multiple demand nodes, ...), the increase in the number of constraints can soon turn these problems unmanageable. Moreover, more complex phenomena like linkages between different countries or dynamic planning quickly increase the size of the model by an order of magnitude.

Large linear systems are usually sparse, the number of nonzero elements representing only a small fraction of the total number of elements of the matrix. This property leads to several interesting features that are now well exploited in commercial codes. Dynamic models also exhibit additional properties of which advantage can be taken in special purpose codes as we shall discuss it now.

Let us consider a capacity expansion model, for the sake of simplicity we shall neglect dismantling of investments: existing capacities in period t can then be written as:

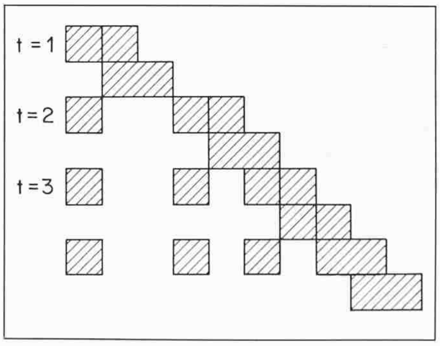
$$Z_t = Z_0 + \sum_{t'=1}^{t} x_{t'},$$

in each period the operations of the system is represented by:

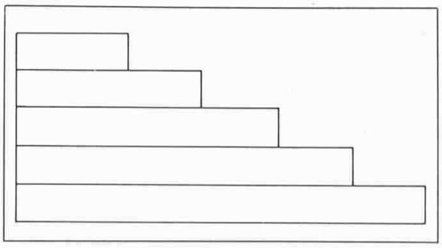
$$A_t U_t + B_t Z_t = b_t,$$

where U_t are the operations variables.

By properly grouping the constraints and the variables, the capacity expansion model can be written so as to display the structure exhibited in the figure below:



Or more simply:



Special techniques based on nested decomposition [8] or block factorization [15] of the basis have been developed for that kind of problems.

Numerical experiments using such methods have been conducted for problems with dynamic structure [9], and it has been shown that significant gains can be obtained when using these methods. A nested decomposition code based on MPSX 370 is currently being developed in order to try to combine the gains of both special purpose methods and efficiently coded LP routines.

References

[1] *Anderson, D.:* "Models for Determining Least Cost Investments in Electricity Supply". Bell Journal of Economics and Management Science, vol. 3, no 1, pp. 267–299 (Spring 1972).

[2] *Baleriaux, H., Jamoulle, E. and F. Linard de Guertechin:* «Simulation de l'exploitation d'un parc de machines thermiques de production d'électricité couplé à des stations de pompage». Revue E (édition SRBE), vol. 5, no 7, pp. 3–24, (1967).

[3] *Carlet, L'Hermitte, E. and D. Levy:* "Methods and Models Used by EDF in the Choice of its Investments for its Power Generation System". Electricité de France, Etudes économiques générales. Paper prepared for presentation at the XXIII International TIMS Meeting, Athens (July 1977).

[4] *Cherniasky, E.:* "Brookhaven Energy System Optimization Model". BNL report no 19569 (December 1974).

[5] *Dantzig, G. B. and S. C. Parikh:* "On a Pilot Linear Programming Model for Assessing Physical Impact on the Economy of a Changing Energy Picture", in "Energy: Mathematics and Models", Fred S. Roberts, ed. Proceedings of SIMS Conference, held at Alta, Utah, July 7–11, 1975, SIAM (1976).

[6] *Delcroix, J. C.:* "Economies d'énergie et bilan énergétique", in "Le chauffage urbain", CIFOP, Charleroi (mai 1977).

[7] *Hermelee, A.:* "Regional Reference Energy Systems". Electric Power Research Institute, topical report prepared by Brookhaven National Laboratory (June 1977).

[8] *Ho, J. K.* and *A. S. Manne:* "Nested Decomposition for Dynamic Models", Mathematical Programming, vol. 6, pp. 121–140 (1974).

[9] *Ho, J. K.* and *E. Loute:* "A Comparative Study of two Methods for Staircase Linear Programs. CORE Discussion Paper no 7801 (January 1978).

[10] *Kemeny, J. G., Snell J. L.* and *G. L. Thompson:* "Introduction to Finite Mathematics", Prentice-Hall, Engwd. Cl., N. Y. (1960).

[11] *Marcuse, W., Bodin, L., Cherniavsky, E. and Y. Sandborn:* "A Dynamic Time Dependent Model for the Analysis of Alternative Energy Policies". BNL Report no 19406.

[12] *MARKAL*, «IEA Energy System Analysis Project». Brookhaven National Laboratory, Kernforschungsanlage Jülich, (1978).

[13] *Linard de Guertechin, F., Lekane, T. and J. Velghe:* "Dimensionnement, fonctions et économies des stations de pompage". Commission économique pour l'Europe, Comité de l'énergie électrique: Colloque sur la couverture des courbes de charge dans les systèmes futurs de production d'énergie électrique, Rome (Italie) (10–14) octobre 1977).

[14] *Vardi, J., Zahavi, J. and B. Avi-Itshak:* "The Combined Load Duration Curve and its Derivation". IEEE Transactions on Power Apparatus and Systems (March-April 1977).

[15] *Winckler, C.:* "Basis Factorization for Block-Angular Linear Programs: Unified Theory of Partitioning and Decomposition Using the Simplex Method". IIASA, RR 74–11 (1974).

Adresse des Verfassers: Dr. *Y. Smeers*, Center for operations research and econometrics, Université catholique de Louvain, 1348 Louvain-la-Neuve, Belgium.

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