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A Paper at the ECE Symposium on Application of Economic-Mathematical Models in the Energy Sector, Alma-Ata September 1973

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A PAPER AT THE ECE SYMPOSIUM ON APPLICATION OF ECONOMIC-MATHEMATICAL MODELS IN THE ENERGY SECTOR, ALMA-ATA SEPTEMBER 1973

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This paper is one of a series describing a multidisciplinary IIASA research program on Integrated Energy System Modelling and Policy Analysis. The initial phase of this research program is focused on the energy systems of three retions: the State of Wisconsin in the U.S.A.; the German Democratic Republic; and the Rhone-Alpes Region in France. The primary purposes of the study are at least three-fold:

(1) To identify existing patterns of regional energy use and supply at appropriate levels of disaggregation.

(2) To compare alternative methodologies for regional energy forecasting, planning, and policy development.

(3) To use the above methodologies to examine alternate energy policy strategies for each of the regions, to explore thèir implications from various perspectives using sets of indicators related to environmental impacts, energy use efficiency, etc., and to evaluate the adequacy of the alternative methodologies as policy tools.

Out of these above three items should evolve improved methodologies for energy systems research and policy analysis. The comparative method, intersecting the different disciplines and nations which would be involved in this project, should serve as a powerful tool to the mutual benefit of the participating nations as well as to other countries facing similar energy problems. It could also serve as a prototype for similar studies on other resources such as materials, water, air, i.e. as a vehicle for development of an approach for improved resource management.

W.K. Foell

Papers in the series describing this research program are:

(1) Foell, W.K. "Integrated Energy System Modelling and Policy Analysis: A Description of an IIASA Research Program" IIASA Working Paper WP-75-38, April 1975.

(2) Dennis, R.L. and Ito, K. "An Initial Framework for Describing Regional Pollution Emissions in the IIASA Integrated Energy System Research Program" IIASA Working Paper WP-75-61, June 1975.

(3) Hölzl, A. and Foell, W.K., "A Brief Overview of Demographic, Geographic, and Energy Characteristics of the German Democratic Republic, Rhone-Alpes, and Wisconsin" IIASA Working Paper WP-75-65, June 1975.

(4) Weingart, Jerome, "Preliminary Data Requirements for a Feasibility Study of the Solar Option in the Rhone-Alpes Region of France" IIASA Working Paper, WP-75-68, June 1975.

(5) Bigelow, J., "Transportation Modeling in the Comparative Energy Study" IIASA Working Paper WP-75-73, June 1975.

(6) Dennis, R., "Data Needs of the Environmental Model for the Integrated Energy Research Program" WP-75-105, August 1975.

(7) Buehring, W.A., and Dennis, R.L., "A Methodology to Assess the Human Health Impact of Sulfur Dioxide Emissions" IIASA Working Paper WP-75-108, August 1975.

(8) Hölzl, A.,"Energy Supply and Consumption for the GDR, Rhone-Alpes and Wisconsin" IIASA Working Paper WP-75-126, October, 1975.

(9) Hedrich, Ufer, Martin, Finon, Pappas, "Preliminary Overviews of Institutional Structures and Models - Information Systems for Energy/Environmental Planning in GDR, Rhone-Alpes and Wisconsin, October 1975.

(10) Hedrich, P., Lindner, K., "A Paper at the ECE Symposium on Application of Economic Mathematical Models in the Energy Sector, Alma-Ata", September 1973.

A Paper at the ECE Symposium on Application of Economic-Mathematical Models in the Energy Sector, Alma-Ata September 1973

Author: Dr. P. Hedrich, Dr. K. Lindner

Subject: Algorithms for the Coupling of Models of the Energy Sector

1. Introduction

The energy sector of each country is a part of the national economic subsystems which directly and to a considerable degree has an influence on the growth rate of the national economy and the increase of national income. Therefore it is a permanent objective to always provide a rational basis for the provision of society with demand-determined supply of energy sources. A tool for the proper achievement of this goal is the application of mathematical-economic models for optimization of the energy sector with consideration of national economic constraints. It is in the interest of society to include the largest possible system in the optimization models. According to the current condition of our understanding, that type of objective can be achieved only with mathematical-economic system models which consider all essential economic, technological, technical, parameters, and to a limited degree also political-economic influences.

2. The Previous Stages in the Application of Mathematical-Economic Models for Long-Term Planning

In the GDR, mathematical-economic models for mid- and long-term planning have been applied with success in the energy economy for many years. From this experience it has been recognized that the optimization of the economically important sub-processes can actually only be achieved through the minimization of expenditures of the entire national economy. However in the use of mathematical-economic models, only limited possibilities exist to characterize the national economy in totality in the necessary depth and quality. Therefore an energy sector submodel was developed which takes into account the crucial national economic constraints. The energy sector was not built up as an administrative-technical unit. It includes all essential processes of energy supply and conversion, energy transport, and the industrial and non-industrial energy uses, as well as the total import and export of energy over a long time period. In the initial stage of the application of the models it was not possible to include the energy sector in a comprehensive manner in one model. For the time being, the industrial and non-industrial processes of energy use could not be presented. Included in a central model in one relatively strong aggregation (but sufficient for central national planning and decisions) were all essential facilities of the primary petroleum processing, the heat and electrical energy production, the coal mining and the coal processing, the production of city gas, and the preparation of natural gas, as well as the import of solid, liquid, and gaseous fuels. As economic objective function, the minimization of social expenditure was used. The model brought together the following aspects:

- the development of demand as a function of time
- the sequence of investments
- the time-dependent shock from investment- and facility expenditures
- into certain cases, the specific utilization of the facilities in successive time periods
- the economically required preliminary retirement of existing plants
- the change in the technical-economic indices as a function of time
- the development of the technology in successive time periods and the constant simple and extended reproduction on the level of the newest technology
- the economic-dynamic view of the selection of facilities by the mutual influence of the indifferent time periods available plants, as both of the previously planned on the later ones and vice versa
- an appropriately concentrated presentation and group formation of the unprocessed energy demand- and -energy conversion plants as well as of the available energy supply resources of the country
- the interdependancy between the plants of the national economic subsystem energy sector
- necessary national economic restrictions

The considered time span amounted 15 years from the end of the current five-year plan and was presented in time differentiated multi-year sections of different durations. As soon as this model had been approved of in practice, one started to develop, according to the same principle, models for the individual branches of the energy sector like: coal mining, the gas economy, the electro-energy- and heat economy and the primary natural oil processing. Consequently, a model was constructed which made it possible to optimize the substitution and optimization part of the industrial and non-industrial energy demand. These models were separated from each other for the use of optimization of single branches. It was however not possible to obtain energy sectors destined, completely balanced evidences corresponding with a total energy sector optimum by means of intensifying evidences of the submodels. Based on the preceding it was decided to develop a model system which would allow to couple the already available models with each other and to utilize them for total energy sector observations.

3. Construction and Application of the Central Mathematical-Economic Model System of the Energy Sector of the GDR

For the construction of a model system one assumes the understanding that the combination of the advantages of all the branch models leads towards a super model, which in practice cannot be controlled. One, therefore, searches for a method which would allow the coordinate the submodels of the branches. A central coupling model system is being developed which, as an entirety and also inside each single model, complies with the same demands, just like the central model of the energy sector. The basic assumption for the harmony of these single results is the uniformity of all submodels with reference to the applied model type, to the objective criterion including its concrete application form, to the considered time span and its subdivision and also to the containing structure of the nomenclatures. In addition to this the goal it was decided to consider the regional aspect on an increased scale. The analysis which, by considering the regional aspect, produced necessary demands to necessitate the construction of models of complex-regional energy supply for regional units of the country, in which all quantities are optimized which can be influenced on a regional basis. The result of this was the need to choose a way which would allow to fast obtain useful sections of evidences with available power and experiences. This way prepared the planning of the constructions of the model system in two stages. The first stage contains the coupling formation of the already available branch models and of the necessary optimization model and also the process of an appropriate coupling algorithm and the testing of this model system in the practical planning activity. The second stage considers to stepwise process complex-regional models for political units of the country and selected cities and industrial agglomeration areas and to prove this by single calculations. It was confirmed that the step-wise processing of single regional models already starts during the construction of the first enlargement stage and is then continued after completion of the itself. The primary stage of enlargement actually appears in the first phase of its practical application, whereas for the second enlargement stage even a larger amount of regional models must be processed.

The first stage of the central model system consists of four main parts. They are:

1) the central optimization model, which contains the entire energy sector in aggregated form;

2) the demand optimization model, which encompasses the substitution and optimization part of the energy demand;

3) The optimization part of the energy sector subsystem for the energy supply production and conversion;

4) The coordination model for the direct coupling of the production optimization models of the energy sector subsystem and of the demand optimization model under consideration of central and total energy sector restrictions.

The following path is hereby covered:

In the first step the consumers' energy demand of the national

economy is defined with the help of the demand optimization model and other research methods. The evidences of this calculation are prepared such that they can, without contradiction, be immediately introduced into the central optimization model as a direct model substance. On this basis one takes into account with the central optimization model the optimal energy supply- and plant structure. Both models, which are considered as a unit, take the shape of an enlarged central optimization model. It is thereby also possible that first the central optimization model is calculated in order to give the demand-optimization model certain allowances. In this connection one cannot speak of a primat of the first step.
The first plan-suggestions for the energy sector subsystem were deduced from the optimization evidences and these indices presented, in which framework they can move around during the optimization. On the basis of this information the energy sector subsystems execute independent optimization calculations, which evidences flow into the central coordination model.

4. Coupling Algorithm for the Coordination of Submodels

From this high labour- and time expenditure, which is connected with a coordination of submodels, arises the necessity to carry out all formal calculation work for the destination of the individual evidences and for the selection, as far as the national economy is concerned, of optimal structures for the energy sector with the help of a suitable calculation process. Such a coupling algorithm must meet the following five basic conditions:

1) The coupling algorithm must illustrate without contradiction the relevant demands of the in-practice applied planning system and assure the general interdependancy of all energy-producing and energy-consuming limits.

2) The coupling algorithm must be practical into high extent, in other words: the expenditure for labour- and calculation time must remain within replaceable limits and the available calculation technique must be applicable.

3) All variants, which are kept available as temporary- and final solutions, must in principle technically and economically be capable for realization in practice.

4) The coupling algorithm must allow a variable application of the single models.

5) The coupling algorithm must guarantee the active cooperation of the planning expertees.

A series of "decomposition process" for the solution of large systems is known from the theory of the linear optimization. Their mathematical validity has been proven at any rate. They are little or not suitable for a practical application in a model system of the energy sector, especially for the fulfillment of the above mentioned five basic conditions. On this basis a coupling algorithm for the practical control of the model system of the energy sector was developed in the GDR. As was already mentioned before, a preliminary balancing resulted with the help of the central optimization model with reference to the possibilities of the energy supply provision. Thereby all necessary national economy restrictions must be considered, like import possibilities, investing capacities, labour power situation, etc. Based on these facts dispersions for the possible energy supply input in the regions and within reach of industrial large customers and also expenditures for the inserted energy supply is deduced. These structures serve as definitions for the application of energy sector regional models and for a demand model of industrial large consumer and simultaneously prevent the appearance of unrealistic energy need structures in the regions, respectively by the large consumers.

With these models primary optimized energy demand structures and primary energy supply input conceptions are obtained under consideration of the fixed limits. These structures however still lack the harmony with the limits of the energy supply acquirement. For this purpose the calculated energy demand structures are inserted in the already applied central optimization model:

$$Z = \sum_{j,k,t} c_{jkt} x_{jkt} + \sum_{i,t} c_{it} i_{it} + \sum_{\mu} z^B_{\mu} p_{\mu} + \sum_{\kappa,\tau} z^B_{\kappa\tau} p_{\kappa\tau} \longrightarrow \text{Min}$$

$$\sum_{j,k} a_{ijkt} x_{jkt} + i_{it} + \sum_{\mu} b_{it\mu} p_{\mu} + \sum_{\kappa,\tau} b_{it\kappa\tau} p_{\kappa\tau} \geq \hat{b}_{it}$$

$$x_{jkt} \lesseqgtr X_{jkt}$$

$$i_{it} \lesseqgtr I_{it}$$

$$\sum_{\mu} p_{\mu} = 1$$

$$\sum_{\kappa,\tau} p_{\kappa\tau} = 1 \text{ (for each } \tau)$$

Z-Value of the objective function (total expenditure)

c_{jkt} specific social expenditure of the energy conversion design j of the subsystem k in a year t

c_{it} specific social expenditure for the import of energy supply in a year t

a_{ijkt} specific coefficient of the profits respectively the inputs of the energy supply i in the plant j of the subsystem k in a year t

x_{jkt} average quantities of the energy conversion laying-out j of the subsystem k in a year t

i_{it} level of the import of the energy supply i in a year t

$z^B_{\mu} z^B_{\kappa\tau}$ social total expenditure of the variant μ, which was calculated in a demand optimization model for industrial large consumers and of the variant κ, which was obtained in a model of the territory τ

$b_{it\mu}$, $b_{it\kappa\tau}$ — Demand for energy supply i in a year t for the variant μ (industrial large consumer) respectively the variant κ of the territory τ

$\hat{b}_{it}$ — Energy demand which supports no optimization

$p_\mu, p_{\kappa\tau}$ — Factors of importance ($0 \leq p \leq 1$)

x_{jkt}, I_{it} — Limitations for the capacity of the conversion plants respectively the energy supply import

By opposing the energy supply production with energy supply input the energy demand variants may, in order to avoid double calculations, only be evaluated with the expenditure which is directly connected with the immediate use of the energy sources. When expenditures for the energy supply production (in the form of prices) are applied by these calculations, they must be eliminated from the total expenditure of the variants.

The calculation of this model already shows a first balanced and optimized energy supply- and plant structure. However, since the central optimization model works with very strongly aggregated indices, a tuning in with the in-detailed model illustrated limits of the energy supply production must follow.

These models contain designs deduced from the central model about the level of the energy supply to be produced by the actual region just as is the case about the expenditure of the energy supply to be inserted. In addition to this it is necessary, that by means of the regions still some variants of the energy supply availability will be calculated whereby the given national economic restrictions must be taken into account, in other words: the upper and lower limit which can or must be obtained (exploited), is likewise centrally pretended. Inside of it exists however full freedom to move about. Various variants are this way created of the energy supply availability, so that a coordination with the energy demand structures of the energy consumer becomes indispensable. For that purpose another central model is applied which , as opposed to the up-to-the-present applied ones, easily of the vectors of the supply-demand of the energy supply exists because of the single regions. The model designed as coordination model has the following appearance:

$$Z = \sum_{\mu} z^{B}_{\mu} p_{\mu} + \sum_{k,\lambda} z^{E}_{k\lambda} \rho_{k\lambda} + \sum_{\kappa,\tau} z^{B}_{\kappa\tau} p_{\kappa\tau} + \sum_{i,t} c_{it} i_{it} \longrightarrow \text{Min}$$

$$\sum_{\mu} b_{it\mu} p_{\mu} + \sum_{k,\lambda} f_{ikt\lambda} \rho_{k\lambda} + \sum_{\kappa,\tau} b_{it\kappa\tau} p_{\kappa\tau} + i_{it} \geq \hat{b}_{it}$$

$$\sum_{\mu} q_{st\mu} p_{\mu} + \sum_{k,\lambda} q_{kst\lambda} \rho_{k\lambda} + \sum_{\kappa,\tau} q_{st\kappa\tau} p_{\kappa\tau} \lesseqgtr Q_{st}$$

$$\sum_{\mu} p_{\mu} = 1$$

$$\sum_{\lambda} \rho_{k\lambda} \leq 1 \text{ (for every k)}$$

$$\sum_{\kappa} p_{\kappa\tau} = 1 \text{ (for every } \tau)$$

$$i_{it} \lesseqgtr I_{it}$$

$z^B_{\mu}, z^B_{\kappa\tau} z^E_{\kappa\tau}$ — Social total expenditure for the variants calculated in the optimization models of the subsystem k ($z^E_{k\tau}$), of the regions τ ($z^B_{\kappa\tau}$) and in a demand optimization model for industrial large-scale consumers (z^B_{μ})

$b_{it\mu}, b_{it\kappa\tau}$ — Need for energy supply i in a year t for the variants calculated in a demand optimization model, respectively in the regions

$f_{ikt\lambda}$ — Variant λ of the output respectively input of the energy supply i in a year t through the subsystem k

$\left\{ \begin{array}{l} q_{st\mu}, \\ q_{skt\lambda}, \\ q_{st\kappa\tau} \end{array} \right.$	Claim of the national economic, respectively energy sector restrictions s in a year t by the single subsystem and regions
Q_{st}	Limitation of the national economic and total energy sector restrictions
p, ρ	Imposing factors $(o \leq p, \rho \leq 1)$
c_{it}	Specific social expenditure for the energy supply import
i_{it}	Energy supply impact

In order to avoid double calculations, the expenditure elements can also here be eliminated from the expenditures of the variants of the regions, elements which attack in other regions.
For each area, the solution of this vector model delivers such a solution which is balanced and optimized in a total energy sectorial manner. It can, thereby, occur that an already by the submodel calculated vector or a combination of two or more primary vectors show up as optimized variants. At the appearance of such "mixed variants" one should always deal with an examimation of the technological and economic possibility for realization of these variants by the planning specialists.
Due to the high level of aggregation of the coordination model, a renewed application of the submodel of the region becomes necessary. Complete submodels are used for this purpose. In order to avoid double calculations, only those factors of the evaluation of the financial expenditure for the input of such energy supply can be eliminated which are drawn from other subsystems. As a limitation for the submodels complete, for the actual area already calculated, variants of the production respectively for the consumption of energy sources serve as a function. Thereto also belong the

optimal variants destined by the coordination model. Contrary to the conventional practice of linear optimization models, these vectors are incorporated into the decision part of the optimization model. Factors which express the importance of the actual variants for the optimum of the entire energy sector, serve as evaluation quantities for these variants. The by the coordination obtained optimal variant is under the existing conditions in this stage of the calculation the most effective for the total system. It is therefore evaluated in the submodels with zero. The application of the remaining variants leads towards a deviation of optimal value. Consequently, the sub-optimal variants in the submodels can be evaluated with the value of this deviation. The "reduced costs" which exist by the linear optimization as a dual solution, can be applied as values of the deviation.

$$z_k = \sum_{j,\ell,t} c_{jk\ell t} x_{jk\ell t} + 0 \cdot \psi_k^* + \sum_{\lambda} r_{k\lambda} \psi_{k\lambda} \longrightarrow \text{Min}$$

$$\sum_{j,t} a_{ik\ell t} x_{jk\ell t} + f_{ikt}^* \psi_k^* + \sum_{\lambda} f_{ik\ell t} \psi_{k\lambda} \geq 0$$

$$x_{jk\ell t} \lesseqgtr X_{jk\ell t}$$

$$\psi_k^* + \sum_{\lambda} \psi_{k\lambda} = 1$$

$(f_{ikt}^* \not\leq f_{ikt\lambda})$

$c_{jk\ell t}$ specific social expenditures of the energy conversion plant ℓ of the plant group j of the subsystem k in a year t

$a_{ijk\ell t}$ specific coefficient of the outputs or the input of the energy source i in a year t of the to plant group j belonging plant ℓ in a subsystem k

$x_{jk\ell t}$	Average quantities of the plant ℓ in a year t
$f^*_{ikt}, f_{ikt\lambda}$	Supply and demand of the energy supply i in a year t by the subsystem k; * = optimal variants of the coordination model, λ suboptimal variants of the coordinate model
$r_{k\lambda}$	"reduced costs" of the coordination model for the variants λ of the subsystem k
$\psi^*_k, \psi_{k\lambda}$	Importance factors

This observation technique allows the selection of a structure of the area which is more effective than the optimal structure chosen by the central model. This is indeed the case when the expenditure decrease in a considered area compensates the long-term expenditure by applying a suboptimal production- and demand structure, which attracts these variants in an entire system.

A second advantage of this observation technique lies in the fact that constantly economic evaluated alternative variants are available when the optimal variants identified by the central model, are technologically of economically in the formally calculated structure impossible to be realized.

In case the optimization calculation in one or more areas leads to the fact that an improved structure of the supply and demand of energy sources appears, then the process of the iterative approach must be continued with the renewed application of the coordination model. The optimal structure of the entire system is reached then when the results in the optimization calculations in the area correspond with the result of the coordination model. An agreement can already be observed in such a structure by which the deviation between total structure and structures of the area does not exceed a given marginal error.

The amount of the necessary iteration steps is usually not large. At performed calculations this amount lies in the neighborhood of three to four steps. This slight amount of iteration steps can, in addition to the way of calculation process, also be brought back to the quality of the previous balancing calculation carried out at the beginning of the fundamental work of the model system.

5. The Application of the Model System and Problems

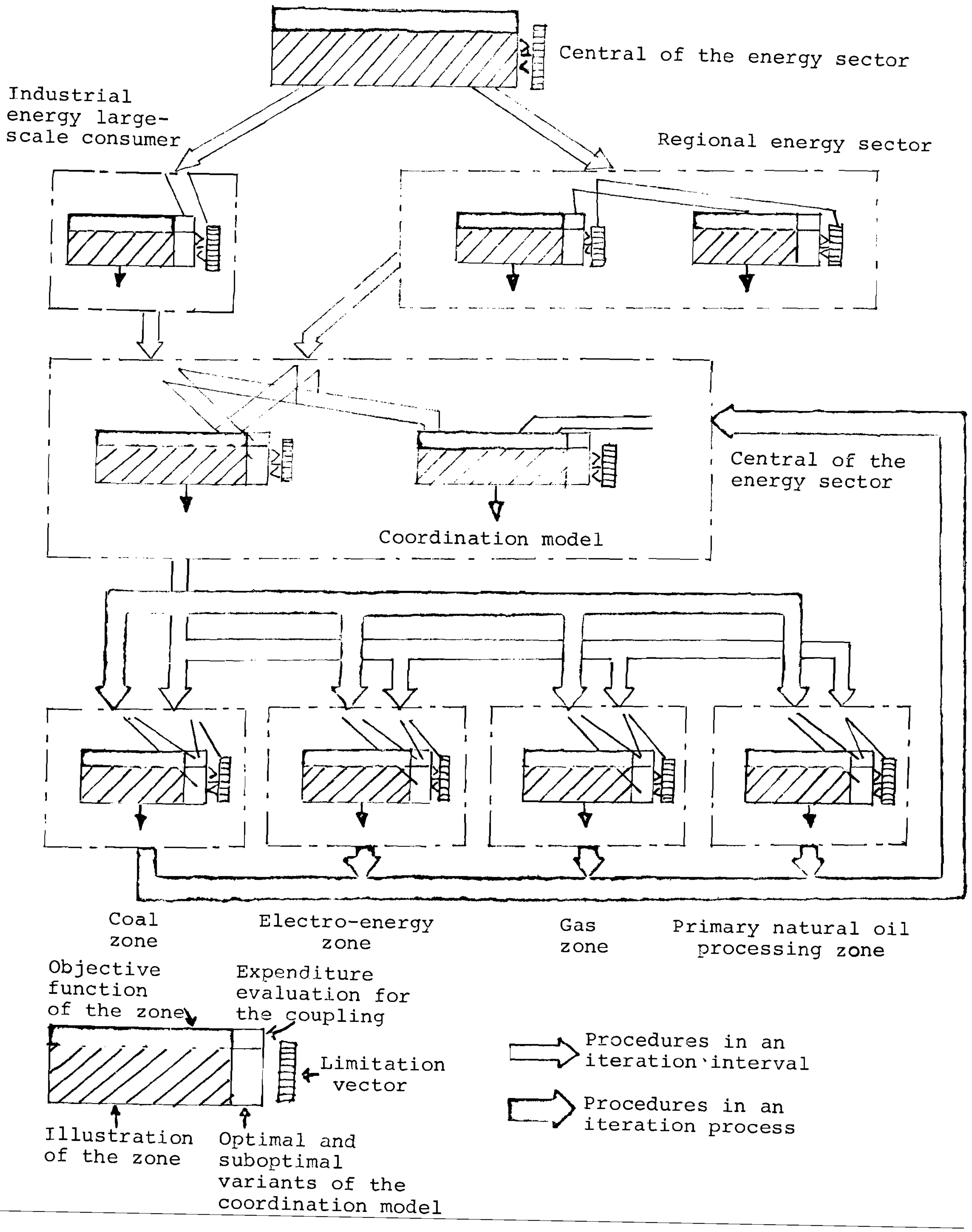
The described development situation of the model system and the still unfinished steps have pointed out that not only the development of such auxiliary methods for the decision preparation, but also of its application, must be stepwise realized, if it must guarantee success. Also with repeated success applied planning auxiliary means with a high level of practicality and adaptability for the actual questions are not automatically suitable for a practical calculation process. Although this statement seems real contradictary, it is correct when it is less related to the model itself but more often to the application of it. One needs more years of experience both of the immediate "manager" and of the decision capable governmental respectively double sliding official functions, before the right proportion is found in dealing with mathematical-economic calculation process of this kind. It is only then valid when the right, in other words practical applicable aggregation level, has already been found. The problem thereby consists, in the first place, of the correct use of model evidences. From these evidences one must, under consideration of differentiated supposed aggregations, understand the recognition, the essential part of reality, and utilize it for decisions to be taken. Herein lies the qualitatively new tasks of the planning experts.

The application of models and model systems should by no means be understood in such a way that, with help of these modern auxiliary methods, ready made plans can be produced by the EDVA. Only by creative processing of the calculation evidences by the specialists' plans are produced and other decision fundamentals, which are nevertheless in each aspect considered calculated in conventional manner, based on a higher level of security of balance and optimality just like the constantly objective existing opinion in the form of an exact calculated objective function. The mistake is quite often made that the scientific collective- or operational research groups, which are commissioned with the construction and application of the models, must obtain themselves both the goal and must also deal with the interpretation. This is only correct for the first steps.

The possible high rationality is only then reached when there is question of a close cooperation by "people entitled to make decisions" and "managers" of the models and when from both sides the understanding is produced for the necessarily different way of viewing of the other. By the merging of both the new quality is created, which is necessary in order to arrive to its rational use from the rejection or adoration of the new technique in this area. The fact that the model system is available does not simultaneously mean that one can refrain from the use of its single model. On the contrary, an economic usage is only then achieved when the application of temporary checking stations are adapted. The entire system or one of its enlargement stages or submdoels can, according to the necessary depth of evidences and -groups, supply the necessary quality of the evidences. An unnecessary exaggerated utilization

can only prevent the permanent and successful utilization, as the optimization itself can again be optimally formed.
When also, with increasing rationalization of the preparation work, of the calculation stages and of the evaluation process, which is only possible by the complex usage of EDVA, the impression appears that people distantiate themselves more and more from this process, then the creative capicity of humanity increases a lot because of the possible people-machine-people-dialogue; this is the case if people understand to shape this process such that they manipulate it analytically, realistically, directively, in other words in a creative controlled manner. This possibility is available, although one needs thereto extensive experience. The in the GDR developed, real simple and workable coupling algorithm is especially suitable for this purpose. For that reason it is allowed to control cooperative collaboration, based on the democratic centralization, of all branches of the energy sector and to utilize extensively their advantages. The previous experiences have pointed out that the coupling algorithm is suitable to couple various systems to each other when the models are shaped accordingly. From the mathematical-methodical point of view the possibility also exists to incorporate in this manner the energy sectors of various countries into one model system. In the first place, the difficulty of this plan lies on the content aspect, in other words, in the available economic conditions of the individual countries. With the progress of the socialistic economic integration increasingly favorable assumptions for such couplings appear inside the RGW. There is still enough time available for the construction and usage of such a multi-lateral model system, since the availability of

total energy sector optimization models in the interested countries is a necessary condition. This problem should not remain unobserved during the future manufacturing in the area of total energy sector balancing and optimization.


Central of the energy sector
Industrial
energy large-
scale consumer
Regional energy sector
Central of the
energy sector
Coordination model
Coal
zone
Electro-energy
zone
Gas
zone
Primary natural oil
processing zone
Objective
function
of the zone
Expenditure
evaluation for
the coupling
Limitation
vector
Illustration
of the zone
Optimal and
suboptimal
variants of the
coordination model
Procedures in an
iteration interval
Procedures in an
iteration process