The Combinatorial Modelling Approach to Study Sustainable Energy Development of Vietnam

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Abstract. The article describes the combinatorial modelling approach to the research of energy sector development. The idea of the approach is to model a system development in the form of a directed graph which nodes correspond to the possible states of a system at certain moments of time and arcs characterize the possibility of transitions from one state to another. The combinatorial modelling is a visual representation of dynamic discrete alternatives and permits to simulate the long-term process of system development at various possible external and internal conditions, to determine an optimal development strategy of the system under study. The formation and analysis procedures of energy development options are implemented in the Corrective software package. The heterogeneous distributed computing environment is needed to compute an energy sector development graph. In 2015 Institute of Energy Science of Vietnamese Academy of Science and Technology performed the study of Vietnam sustainable energy development from 2015 to 2030. Based on data of this study the combinatorial modelling methods are applied to the formation and analysis of Vietnam energy development options taking into account energy security requirements. The created Vietnam energy sector development graph consists of 531442 nodes. It is computed on the cluster located at Institute for System Dynamics and Control Theory of Siberian Branch of Russian Academy of Science (Irkutsk) under control of the Orlando Tools software package. The found optimal path of Vietnam sustainable energy development provides the minimum costs of energy sector development and operation.

Keywords: Combinatorial modelling·Energy sector·Decision support·Distributed computing environment.

1 Introduction

The study of long-term energy development with regard to uncertainty (ambiguity) of the initial information and development conditions [1] should be conducted on the basis of general energy research approaches [2, 3] with the use of special methods, models, databases and software. The models should consider rather long time period (30-40 years) and distinguish several stages in the development and operation of energy systems. Also models should explicitly consider discreteness of the energy facilities development options. Tools to generate and analyse energy development options must be well-founded and flexible. They should be established on some general organizing research, algorithms to create and choose energy development options.

It is impossible to describe and test all distinctive combination of external conditions and energy development options within frames of an energy sector model taking into account uncertainty, energy security threats and other factors. It leads to a huge number of possible energy sector states and takes a lot of time to generate and analyse using usual methods of research. To deal with this issue the combinatorial modelling approach is used. The combinatorial modelling is a visual representation of dynamic discrete alternatives and permits to simulate the long-term process of system development at various possible external and internal conditions, to determine an optimal development strategy of the system under study.

This article describes the software that implements some combinatorial modelling approach procedures and considers their application to study some problems of sustainable energy development of Vietnam.

2 The Energy Sector Model

The balance economic-mathematical model [4] evaluates the energy sector state at a certain time period with regard to energy security (ES) requirements [5-7]. The model possibilities are quite close to MARKAL [8], MESSAGE [9], EFOM-ENV [10], TIMES [11], Balmorel [12] and others. The model allows:

- Considering a whole energy sector from the production of energy resources to final consumption in the various economic sectors including all stages of energy transformation;
- Investigating energy technological and territorial structure development.

The energy sector model is the following linear programming problem:

$$AX - \sum_{t=1}^{T} Y^t = 0, \quad (1)$$

$$0 \leq X \leq D, \quad (2)$$

$$0 \leq Y^t \leq R^t, \quad (3)$$

where t is a category of consumers; X – the decision vector whose components represent the intensity of energy facilities usage (storage, production, transformation and transmission of energy resources); Y_t – the decision vector whose components characterize the energy resource consumption for different categories t; A – the matrix of facilities technology factors (production, transformation) and transmission of energy resources; D – the vector that determines technically possible capacities of production, transformation and transmission facilities; R_t – the vector that defines energy resources demands of the category *t*.

The objective function is as follows:

$$(C, X) \ + \ \sum_{t=1}^{T}(r^t, g^t) \ \rightarrow min \tag{4}$$

The first component of this objective function reflects the operation costs of the energy sector. The vector *C* contains unit functioning costs for the existing, reconstructed, upgraded and newly built production, transformation and transmission facilities.

The second component represents the losses due to the energy resources deficit for the different consumer categories. The energy resources deficit g^t of the category *t* is equal to the difference between R_t and Y_t. Vector r^t consists of the components called "specific losses" for consumer of category *t*.

3 The Combinatorial Modelling Approach

The procedures of formation and analysis of energy development options are based on the representation of components belong to an investigated system in the form of a directed graph. The graph nodes correspond to the possible states of components in the certain moments or cuts of time. The graph arcs define the admissibility of transitions between states. The research of the whole system development is performed by analyzing various combinations of states and transitions of particular components. This approach is known as combinatorial modelling [13].

A component is a structural unit of the system under research. It may be a factory, power plant, set of the similar energy sources or a consumer category. The degree of aggregation of the energy production or consumption facilities depends mostly on the goals of study and data base possibilities.

The first step of the combinatorial modelling approach is to describe the basic scenario of energy development to investigate as a graph with one node for each cut of time (see Fig. 1). These nodes contain the essential information to create new possible states of the energy sector.

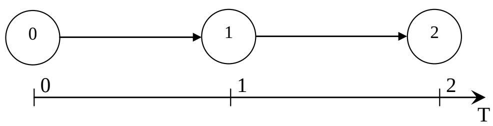

Fig. 1. Basic scenario of energy sector development

At second step the infrastructure of energy sector is separated into several components by territorial or industrial criteria. For the each component a development graph is built. It contains changes of energy facility parameters at the considered time period. The development graphs of two energy facilities are shown on Fig. 2. The source nodes corresponding to time 0 do not have numbers because they will not participate the next generation of the energy sector graph.

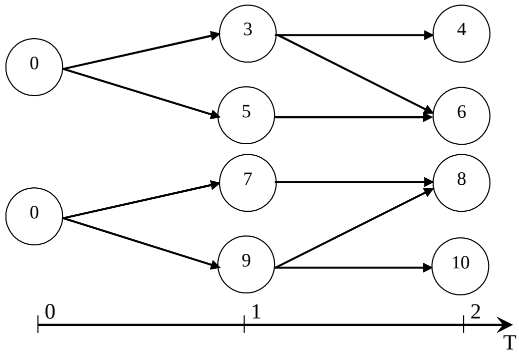

Fig. 2. Development graphs of 2 energy facilities

The third step is combining data of reference graph with information of different component graphs belonged to the same moment in time. This results in the set of possible states of energy sector for each moment in time. The created states (nodes) are linked by transitions (arcs) to form an energy sector development graph.

An energy sector development graph shown on **Fig. 3** is created by means of combination of nodes and edges of the graphs on **Fig. 1** and **Fig. 2**. The number of generated possible energy sector state is shown inside circle on **Fig. 3**. The numbers above a circle are combination of the graph nodes on **Fig. 1** and **Fig. 2**. The beginning of all paths in the generated energy sector development graph is common initial node at moment 0.

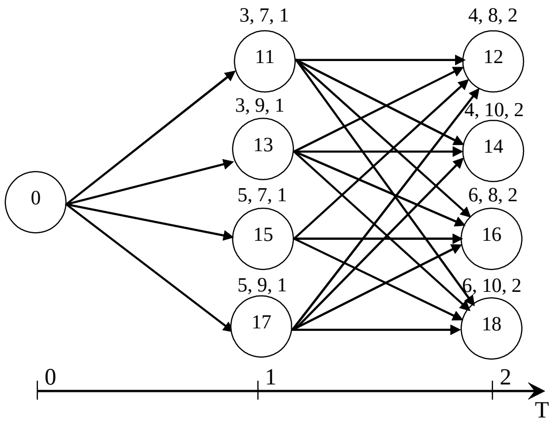

Fig. 3. Energy sector development graph

The forth step is to check the validity of nodes and arcs of the energy sector development graph since not all possible energy sector states and transitions can be valid. For this purpose, there are system-wide constraints in the combinatorial modeling. Among them it can be distinguished two types:

1. Logical conditions. Some development alternatives of a component can depend on the implementation of certain development variants of other components.
2. Balance and other design constraints. These are restrictions on the available raw resources and products at every cut of time and transition. They can be defined in the form of balance equations or inequalities.

Lists of pairs of incompatible nodes are used to implement logical conditions. A couple of incompatible nodes is a pair of nodes of the different component graphs and their combination in a possible system state is not possible or does not make sense for some reasons.

The model of energy sector described above is of the second type of system-wide constraints. The admissibility of an energy sector state depends on the correctness of the decision results.

If ES requirements exist then ES status of a possible energy sector state is estimated by means of ES indicators. ES indicator value is calculated on the basis of the economic-mathematical model of energy sector decision results. The ES status is determined by comparison of ES indicators values and thresholds.

The energy sector development graph shown on Fig. 3 has four nodes that did not pass the validity check (see Fig. 4).

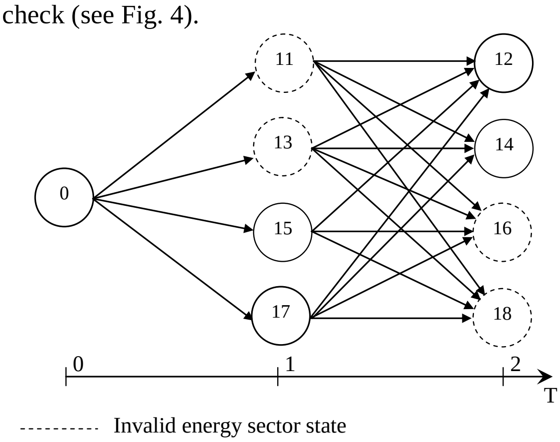

Fig. 4. The validity check of energy sector states

The fifth stage is to build a graph containing valid states and transitions. States and transitions that are unreachable from the initial state are determined during the passage from the initial node to the end nodes. After that blind states and transitions are determined during the reverse passage. It is impossible to build a path from the initial node to the nodes at last time moment with blind states and transitions. The invalid, unreachable and blind states and transitions are removed from the graph which contains possible energy sector states and transitions.

At the last stage a set of optimal and close to optimal paths is determined by finding shortest paths from the initial node to end nodes with a criterion.

The graph which consists of valid energy sector states and transition is shown on Fig. 5. It was made from the graph shown on Fig. 4 where an optimal way to ensure minimum costs of energy sector development and operation is presented by the bold lines.

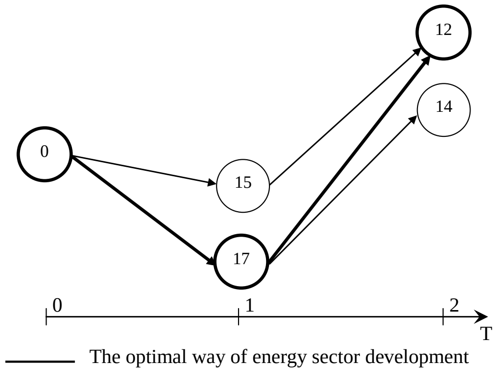

Fig. 5. The development graph with valid energy sector states and transitions

The main issue of the combinatorial modeling implementation is to deal with large number of the simulated system states and transitions. It grows exponentially with the increasing number of system components and their states. That is why the combinatorial modeling approach is usually used with distributed computation technologies [14].

4 The Software Package Corrective

The above procedure of formation and analysis of energy sector development are implemented in the software package Corrective. It consists of the following modules:

1. module m_1 to design basic scenario of energy sector development to study,
2. module m_2 to create energy sector development graph,
3. module m_3 to check the validity of a possible energy sector state (node of development graph),
4. module m_4 to support expert analysis of energy sector development paths.

The scheme of information and logical links between modules of software package Corrective is shown on Fig. 6 in the form of bipartite directed graph where modules m_1, m_2, m_3, m_4 are black ovals.

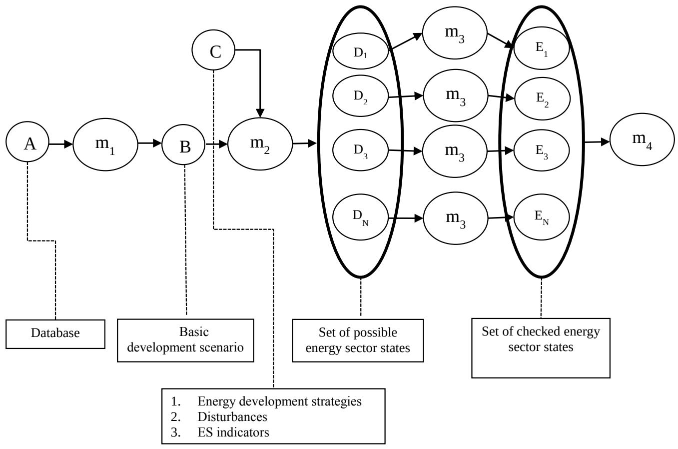

Fig. 6. The logical scheme of software package Corrective

5 Making Scalable Computations With The Software Package Orlando Tools

The Corrective software works in a heterogeneous distributed computing environment (HDCE) by means of the software package Orlando Tools [15]. It is a set of tools to create scalable applications. The architecture of Orlando Tools consists of the next main components: the user interface, the model designer, the knowledge base, the executive subsystem and the computations database (see Fig. 7).

The interface is implemented as a Web application and provides access to other components. The aim of the model constructor is to make the declarative specification of computational knowledge about modules of an application that solves the domain specific tasks, the knowledge of modular structure of a domain specific model and algorithms, the knowledge to support the decision making to choose the optimal computational algorithms depending on the HDCE conditions as well as the software and hardware parameters and administrative characteristics of the HDCE nodes. The model constructor provides the textual (as an XML document) and graphical (as diagrams) notations of the domain specific model. The model is stored in the knowledge base.

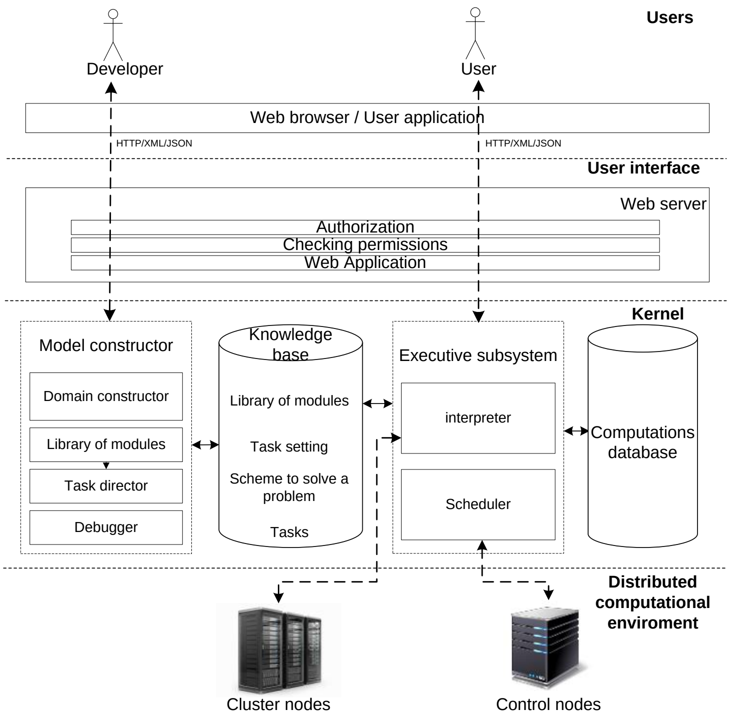

Fig. 7. The architecture of Orlando Tools

The executive subsystem includes an interpreter of the schemes to solve the domain specific tasks and a scheduler. The interpreter processes the control structures and executes the schemes to solve the domain specific tasks. The scheduler performs the schemes decomposition for the better HDCE communication optimization and load balancing. The decomposition can be made before the computation starts or immediately during the computation process. The initial data and the solution are stored in the computations database.

The parameters and operations of the Corrective package domain area as well as their interrelationships are shown on Fig. 8. The rounded rectangles are modules m_2, m_3, m_4. The ovals inside a rectangle are the module input and output parameters. The folder parameter is a temporary folder to keep the intermediate data. Square brackets in the name denote that the operations with this parameter or module can be done in parallel. The output of the module m_4 is a result archive file.

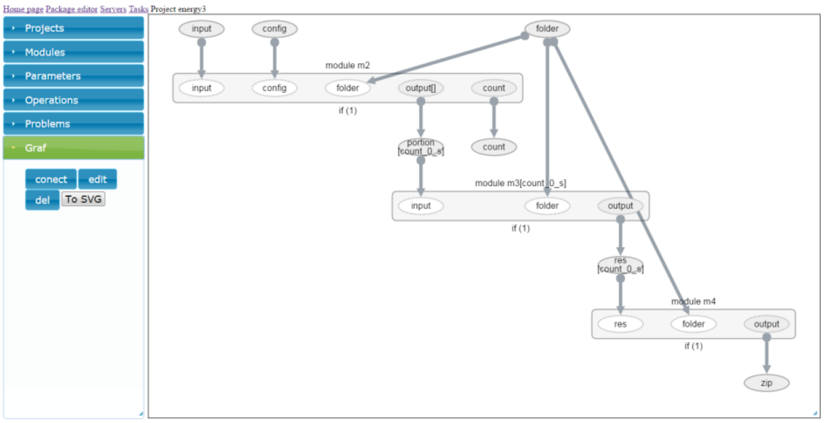

Fig. 8. The Orlando Tools model constructor with the Corrective package domain scheme

6 Modelling Sustainable Development Of Vietnam Energy Sector

The Vietnam energy sector model was developed from 2011 to 2015 on the basis of the energy sector model presented above during the joint research conducted by the Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Science (ESI SB RAS) and the Institute of Energy Science of Vietnamese Academy of Science and Technology (IES VAST) [16].

In order to analyse the characteristics of the key socio-economic regions the Vietnam energy sector structure and some other related issues the supply and demand balance are calculated according to eight regions: Red River Delta, Northeast, Northwest, North Central, South Central Coast, Highlands, Southeast and Mekong Delta. Input data includes energy supply (costs and value of production, import and export), conversion and transportation of energy, energy consumption by types of energy - fuel including coal, oil and gas and power system. Specifically, the regional parameters of production capacity, costs of production, transport capacity, transport costs are built on the basis of data from the individual production and transportation facilities. The data on regional energy consumption is extracted and calculated on energy consumption of five key economic sectors: industry, agriculture, transportation, commerce- service and residential.

In 2015 IES VAST with the help of module m_1 [17] investigated the sustainable energy development of Vietnam from 2015 to 2030 with regard to the energy security requirements. The energy development scenarios are assessed on energy security and sustainable development criteria. These scenarios should meet the national energy demand for the socio-economic development; apply the suitable and efficient energy technology, minimize the environmental impacts from the energy system, and achieve the cost effective energy system development.

The different energy development scenarios for the period 2020-2030 were built on the basis of capacity fluctuation of the following energy facilities: domestic coal production capacity (baseline, increase by 10 %, decrease by 10 %), domestic natural gas production capacity (baseline, increase by 10 %, decrease by 10 %) and domestic hydropower generation capacity (baseline, increase by 10 %, decrease by 10 %).

In the optimal way, natural gas capacity increases by 2020 to meet the national energy demand than follows the base scenario by 2025 and 2030. Hydropower capacity remains stable for the whole period 2020-2030, while the coal capacity reduces by 10% by 2020.

Below the algorithms for combinatorial modeling were applied using the same assumptions and data for the formation and analysis of Vietnam energy development [18, 19].

At the first stage, the basic energy sector development graph was created. At the second stage the component development graphs were built for the pairs of industries and regions of Vietnam which marked with "+" in the Table 1. A typical component development graph is shown on Fig. 9 where the component capacity fluctuation is shown in the circles.

Table 1. Energy industries and regions of Vietnam

Region	Domestic coal production	Domestic natural gas production	Domestic hydropower generation
Red River Delta	+		
North East	+		+
North West			+
North Central Coast		+	+
South Central Coast			+
Central Highland			+

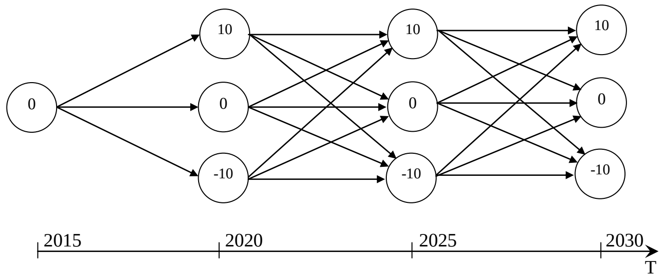

Fig. 9. A typical development graph of Vietnam energy industry

At the third stage, an energy sector development graph that consists of 531442 nodes is created. At the next stage, the computational experiment on the new energy development graph is performed with HDCE which includes nodes of the high-performance cluster Academician V.M. Matrosov [20]. The cluster is located at Institute for System Dynamics and Control Theory of Siberian Branch of Russian Academy of Science (Irkutsk) and includes 60 computational nodes T-Blade V205S. Each computational node contains two AMD Opteron 6276 «Interlagos» processors with 16 cores.

At the fifth stage, the optimal path is found with minimum costs of development and operation criterion where the natural gas production increases and the coal production reduces for all time moments.

The creation of the energy sector development graph and its computation on 40 cores took 7 hours 4 minutes. The computational time of one possible energy sector state was about 0.0365 seconds.

7 Conclusions

Traditionally while comparing development options by multiple-criteria decision analysis such as the analytic-hierarchical approach used by IES VAST experts the researchers usually compare the rather small number of options. Usually a choice depends on intuition and experience of the researchers. However, such a limited choice always reflects some subjectivity which reduces the evidence level of the obtained results.

The advantages of the combinatorial modelling are the clarity and compactness of representation of a modelled system development options in the form of a directed graph. A graph clearly illustrates as differences of various system development paths as their common states and transitions.

By the advantages are achievable with the completeness of their description. The traditional approaches to compare the development options based on the multi-criteria methods usually permit a researcher to choose a few options only. A choice depends on the researcher’s intuition and experience. Such a choice even if it is right always reflects certain subjectivity and thus depreciates the level of result proof.

A result set of the admissible system development paths can be used in many forecasting tasks where, for example, it’s necessary to take into account the uncertainty issue. Among the admissible system paths one can choose not only the best way but also paths close to it according to specified criteria.

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