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Application of multi-objective and robust optimization methods for a comparative evaluation of nuclear energy system deployment scenarios

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Abstract

This article describes additional computational modules developed for the IAEA energy planning software MESSAGE. These modules are intended for multi-objective and robust optimization of deployment scenarios for nuclear energy systems with account for the uncertainties in technical and economical parameters. The authors present the results of application of the developed modules for the studies on multi-objective optimization of the nuclear energy structures. The developed set of computational modules makes it possible to find a compromise between conflicting system factors determining the nuclear energy development, carry out a comparative multi-criteria analysis of development options with due account for their evolution, specific features of the nuclear fuel cycle structure and organization as well as the most important system constraints.

Application of the multi-objective and robust optimization methods together with statistical methods for uncertainty assessment may help formulate more substantiated judgments about the attractiveness of possible nuclear energy structures by comparing various development options. These IAEA based software tools make it possible to determine nuclear energy development strategy options due to a combination of conflicting systemic factors taking into account uncertainties in the main technical and economical parameters.

Keywords: Energy planning; Multi-objective optimization; Nuclear energy system; Nuclear fuel cycle; Uncertainty.

Introduction

Evaluating the efficiency of different directions for improvement and optimization of nuclear energy object parameters, technologies and structures is a multi-criteria problem [1–4]. The efficiency of a nuclear energy system (NES) is determined by a wide spectrum of criteria characterizing safety, resource consumption, financial performance, risks of unauthorized proliferation and waste management. In determining priorities in the development of nuclear technologies and comparing innovative NESs, it is necessary to consider the conflicting nature of the criteria because an improvement in one of the criteria causes, as a rule, a deterioration of values in the others.

The limited scope of applied calculation models makes it difficult to obtain the final result which would determine the most efficient NES development option since up to now there has been no widely accepted algorithm or methodological approach in this field. A solution to the problem of evaluating the efficiency of different directions for improvement and optimization of the parameters of nuclear energy objects and technologies in a multi-criteria context would make it possible to search for coordinated technical, institutional and structural solutions, determine compromise system parameter values in the context of benefit-risk balance, and carry out a comparative multi-criteria analysis of possible alternatives with a quantitative evaluation of their strengths and weaknesses.

To increase the validity of judgments formulated on the basis of calculations, an uncertainty analysis is required. The re-

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sults of an individual calculation are not absolutely accurate as they always contain uncertainties. Therefore, it seems important to determine the interval where the estimated value can be found which characterizes the system response to changes in the calculation model parameters within the limits of their uncertainties.

There arose a necessity for developing a special set of tools for studies on the multi-criteria evaluation of NES efficiency at the national, regional, and global levels in order to determine coordinated development strategies due to a combination of conflicting systemic parameters with account for uncertainties of the main technical and economical parameters. For the purposes of developing methods, algorithms, and software systems for a multi-criteria efficiency evaluation of directions for improvement and optimization of the parameters of nuclear energy objects and technologies, additional modules for the IAEA energy planning software MESSAGE were developed [5,6] which expand the spectrum for its potential applications. These modules implement multi-objective optimization for the comparison of NES efficiency and assessment of uncertainties in the calculation model parameters which affect the calculation results. The paper presents a brief description of these modules and a demonstration of the calculation results obtained using the software tools developed for optimization of NES structures in the context of a multi-criteria evaluation and uncertainties.

Methods for multi-objective optimization and uncertainty impact assessment

Multi-objective optimization is the domain of multiple-criteria decision-making where the number of options is not explicitly given. In each particular case, any possible option can be found by mathematical modeling. As a rule, the number of possible options is either infinitely large i.e. uncountable (when certain model variables are continuous) or very large i.e. countable (when all model variables are discrete).

A wide spectrum of methods was developed for solving multi-objective optimization problems. One of the approaches to the classification of these methods is based on the ways of using information about the decision-makers' preferences. According to this classification, a priori, a posteriori, adaptive, and interactive method classes are distinguished [7]. The majority of contemporary multiple-criteria decision-making methods are based on the sets of Pareto-optimal solutions.

Taking into account uncertainties in the technical and economic parameters and performance features of NES objects and technologies, a solution to parameter optimization problems in a multi-criteria context may increase the validity of judgments formulated on the basis of performed calculations. Uncertainty accounting may be based on interval algebra, fuzzy sets, as well as probabilistic and Monte-Carlo methods.

Application of robust and stochastic optimization methods [8,9] is a promising direction for the development of optimization energy planning models which may help solve a number of problems associated with taking account of uncertainties within the classic deterministic optimization methods requiring significant volumes of accurately specified initial data, which is near-impossible. In many cases, even a small uncertainty in the initial data can make a solution to the problem infeasible.

Both stochastic and robust optimizations are mutually complementary approaches to taking account of data uncertainties in optimization problems, with each of the approaches possessing its own merits and demerits. These optimization types make it possible to find solutions which are 'immune' to data variations within their uncertainty ranges. In the case of stochastic optimization, the uncertain data values are assumed to be random and following the known distribution law. In the case of robust optimization, the law of distribution of uncertain values is considered to be unknown. The solution to the stochastic optimization problem will be correct with a certain probability, whereas, in the case of robust optimization, the solution will be optimal and permissible for any uncertain data values from the given set.

To implement the methods of multi-objective optimization and account of uncertainties for the dynamic optimization tasks, serial calculations should be carried out with different NES model variable parameter values. Developing a dynamic NES model is a separate task which can be solved using a large number of available software packages. One of such packages used for conducting research in the field of NES and NFC is the IAEA software package MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts), a large-scale dynamic system engineering optimization model, developed for middle- and long-term energy planning, energy politics analysis and scenario development [5,6,10]. In the early 2000s, the IAEA launched a project on providing support to the Member States in the practical implementation of the MESSAGE software package. For this purpose, a user interface was created for the latest version, MESSAGE V, acquired from the International Institute for Applied Systems Analysis (IIASA, Austria). This interface allows the users to formulate linear programming problems, find optimal solutions, and process the calculation results.

Modules for multi-objective optimization and uncertainty accounting within the message software package

In view of the growing need in the software tools for solving the optimization problems of NES structures in a multi-criteria context, in 2009, it was decided to develop additional modules for multi-objective optimization and uncertainty accounting within the MESSAGE software package [11]. Six modules expanding the spectrum for possible MESSAGE applications were developed and realized as stand-alone software products.

A set of basic computational models was developed for once-through and closed NFCs (U, U-Pu, U-Pu-Th) within the MESSAGE package adapted for multi-objective optimization problems and material flow calculations in the NFCs of steady-state and developing NES at the national and global