System and Decision Sciences at IIASA in 1980 and now: A methodological perspective

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Preamble. System and decision sciences are very broad notions. IIASA was one of few institutions in the world that engaged with these disciplines nearly since their inception. This document briefly reviews how system and decision sciences were understood at IIASA in the early days of the Institute, some aspects of how our current work builds on the past and what is different. This paper is by no means a comprehensive review. Rather, it focuses on selected aspects and represent the opinion and personal perspective of the author.

Wienbicki & Young (1981) provided a very useful account of the development of the System and Decision Sciences (SDS) Area at IIASA (in the first several years of IIASA's existence it was called Methodology Project) in 1973-1980. Over these eight years, the SDS Area focused its research on mathematical methods to support decisions including mathematical programming, control theory, and decision theory. In addition to the methodological focus, the SDS Area developed novel economic models addressing various questions from natural resource management to labor supply and unemployment.

Mathematical methods relevant for model-based decision support. Most approaches relying on models to support decisions employ the optimization paradigm. The assumption is that a decision maker aims to optimize a certain objective function. In economic models, it is often a cost or economic welfare. Decision analysis typically deals with situations when a decision maker has to choose from a finite number of options. An example of a decision analysis problem would be a problem of choosing where to build a factory from three possible locations. Mathematical programming addresses the problems in which decision variables are vectors that can take continuous values. For example, this can be a problem of land use planning in which a decision maker would like to distribute land for various purposes such as growing different crops, grazing, recreation etc. Finally, (optimal) control theory considers problems in which decision variables are functions. A typical example here is an (endogenous) economic growth problem in which a decision maker allocates the produced output between consumption and investment; while the current consumption increases his current welfare, investment allows to produce more – and hence also consume more – in the future; here the decision variable is the consumption/investment ratio as a function of time.

Naturally, a decision maker can have several objectives, in which case the decision-making problem turns into is a problem of multi-criteria analysis/optimization. Multi-criteria analysis and optimization problems are addressed within the decision theory. A problem may involve several decision makers acting strategically without coordination – such situations are covered by the game theory. Finally, in all these decision-making situations the decision maker can face uncertainty regarding the model parameters. In case probabilistic distributions are available to describe uncertainty in model parameters, stochastic optimization or stochastic programming can be used to derive solutions.

Optimization methods at IIASA in 1973-1980. In what concerns mathematical programming, in 1973-1980, the SDS Area focused on solving large scale linear programming and integer programming problems. In what concerns decision theory, the emphasis was on multiple-objective optimization, multi-person decisions using game theory, fair allocation, decision making under uncertainty, as well as decision making within hierarchical structures. In addition to these, SDS researchers worked on the development of the non-smooth and non-convex optimization; towards the end of 1970s – beginning of 1980s, they started working on stochastic optimization.

Wienbicki & Young (1981) highlight the fact that the SDS Area not only focused on methodological research as such, but also provided input to the work of other groups at IIASA. Among the examples they mention in this context are an energy planning model developed in collaboration with the Energy Project; a rigorous treatment of Holling's resilience concept using dynamic systems theory – in collaboration with the Ecology Project; non-smooth optimization techniques developed by SDS researchers and used by researchers of the Food and Agriculture to solve their world food trade model – to name just a few.

Optimization methods at IIASA today. Mathematical programming that solves large-scale linear optimization problems is a major workhorse of mainstream IIASA models including GAINS and MESSAGE. Other abovementioned methodologies are being further developed and used at IIASA – often in collaboration with external partners. I highlight three directions here.

Uncertainty. In collaboration with researchers from the Institute of Cybernetics, National Academy of Sciences of Ukraine, IIASA researchers continue to advance stochastic programming approaches (e.g., Ermoliev and Norkin, 2016); stochastic programming is used to derive solutions that would be robust with respect to uncertainty in IIASA's land-use model GLOBIOM hosted by IIASA's ESM Program (e.g., Ermolieva et al., 2016). In collaboration with researchers from the Aalto University, Finland, IIASA's researchers advance and apply a method from decision analysis – Bayesian networks with uncertainty – to inform decisions related to managing business platform ecosystems which is a rather new and poorly understood phenomenon (Vilkkumaa et al., 2018). These two examples demonstrate the general trend of the current times to recognize the role of uncertainty and include uncertainty in the model design. While the theoretical foundations of the stochastic optimization approach began to develop already 40 years ago, it has not yet become standard in applied modeling addressing sustainability. IIASA's ASA Program aims to promote the stochastic optimization approach and puts special emphasis on demonstrating benefits of such solutions in applied case studies.

Stakeholder engagement. In collaboration with researchers from Stockholm University, Sweden, IIASA researchers apply approaches of multi-criteria analysis in stakeholder processes; one important case study that was conducted in collaboration with researchers from the University of Jordan, Jordan developed recommendations for energy transition in Jordan (Komendantova et al., 2018). This example is one of many where IIASA is practicing participatory approaches to improve the feasibility of derived solutions. While the importance of stakeholder engagement for realistic policy design was recognized already several decades ago, the technical means to use formal models as a part of a stakeholder process were very limited back then. At present, IIASA experiments with various ways of infusing quantitative modeling into soft systems analysis across various scales from local to regional, to national and even to global. ASA research aims to enhance the rigor of participatory process methods to increase their credibility and trust in recommendations they provide.

Stylized models. In collaboration with researchers from Steklov Mathematical Institute, Russian Academy of Sciences and other Russian partners, as well as with researchers from the Technical University of Vienna, Austria, IIASA researchers advance methods of optimal control theory; in particular, they develop a rigorous and comprehensive theory of optimal control over infinite planning time horizons, which is necessary for economic models (e.g., Aseev and Veliov, 2017). Optimal control approach is used to analyze various stylized models dealing with a broad spectrum of economic issues pertinent to the sustainability challenge, including the use of natural resources (e.g., Manzoor et al, 2014). Due to the continued technical limitations of the state-of-the-art control theory approaches, they can only be applied effectively to small-scale models. That is why the initial enthusiasm of researchers who discovered many new general facts and patterns about economic processes using control theory in 1960s-1980s was reduced thereafter. Many scientists were of the opinion that the power of optimal control was nearly exhausted. However, currently one can observe a growing interest in and recognition of stylized and medium-complexity models in general and optimal control methodology to investigate them in particular. New areas of application are emerging; notably, currently one witnesses a boom of publications analyzing compartment models in epidemiology in response to the COVID-19 crisis. IIASA researchers are also working actively in this direction at the moment.

All in all, the close contact and dialogue between mathematicians and applied scientists enabled by IIASA allows mathematicians to see the needs of applied problems and steer the development of the methods in these directions. As the method development is time- and effort-consuming enterprise with a very uncertain rate of return, under the current funding model of IIASA it rarely happens fully in-house. Part-time involvement of mathematicians as well as research visits to IIASA allow a sufficient exposure and provide food for thought, while the main work is often conducted at home universities. Maintaining this mechanism enhanced with a clearer accountability and attribution would help demonstrating the value of this approach to NMOs.

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