CMFRI

Winter School on

Towards Ecosystem Based Management of Marine Fisheries – Building Mass Balance Trophic and Simulation Models

INFORMATION ONLY

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Technical Notes

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SYSTEM ANALYSIS

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When addressing an issue in fisheries we may have to consider many interacting biological, economic, social and legal factors. Management plans ignoring one or other of these and concentrate on the remaining will fail when executed. Systems analysis is both philosophical approach and a collection of techniques developed explicitly to address complex problems. Its origin can be traced to Second World War by the military to deal with complex logical problems. It was later successfully applied in the fields of engineering, industrial dynamics, business management, economics and recently in biology, ecology and renewable natural resource management. Systems analysis emphasizes a holistic approach to problem solving and use of mathematical models to identify and simulate important characteristics of complex systems. In systems analysis complex problems are quantitatively addressed.

What is a system?

There are several different definitions of system in current use:

- A system is an organized collection of interrelated physical components characterized by a boundary and functional unity.
- A system is any set of objects that interact.
- It is a collection of "communicating" materials and processes that together perform some set of functions.
- A system is an interlocking complex of processes characterized by many reciprocal cause-effect pathways.
- Dictionary definition: An organized or connected group of objects.
- A set or assemblage of things connected, associated, or interdependent, so as to form a complex unity.
- Any phenomenon, either structural or functional, having at least two separate components with some interaction between these components.
- A more general definition is "any object whose behaviour is of interest". (Here, what affects the system, but lies outside its limits, is part of the system's environment.)

The principal attribute of a system is that we can understand the system only by viewing it as a whole. A system is chosen for a particular purpose like "to answer a question", "to demonstrate a theory", "to classify part of the natural world" etc. In ecology examples of system are communities, ecosystems, populations, individuals and even part of a body like rumen of a deer.

The two most useful properties that systems have are:

1. Systems may be nested
2. Systems at the same level of resolution may overlap.

For example, an individual is a part of a population; a population is a part of a community and so on. A system that we define to study the population dynamics of a fish species will overlap with the system that we define to study the population dynamics of another fish species if they posses pray-predator relationship. For a problem at hand we must take great care to define the boundaries of the system of interest. The philosophy of studying the total behaviour of some complicated system is termed **Holism**. The general systems theory is based on the idea that complex systems have characteristics in common that make them an independent object of scientific inquire. Knowledge of individual processes and elements is not able to explain vital phenomena. It is necessary to discover the laws of biological systems at the different levels of organization.

Systems around us

1. The heating system of this building.
2. The ignition system of an automobile.

Each of these systems has components that themselves could be considered as systems: e.g. a thermostat or a spark plug. Each of these systems is a part of a larger system, i.e. the building, or the engine (which in turn is part of the automobile). Thus any particular system that we may wish to study is part of a hierarchy of other systems. It is up to us to choose the level that we work with, and our first order of business is to define the spatial, temporal, and conceptual limits that we wish to address. We are mostly concerned with the larger systems of nature, including the ways that man interacts with nature. Such systems are normally called ecological, sociological, or economic, and they display the same types of interactions and generalities of scale as physical systems display.

mouse: nervous system interacts with circulatory system, etc.
population: many mice
community: mice population + other animals + plants + microorganisms
ecological system: community + nonliving associates:
ecosystem: Generally for a unit of landscape (e.g. ponds)
biome: very large ecosystems of subcontinental dimensions and strong biotic continuity. (e.g. the boreal forest)

Ecosystems tend to be a convenient level to study some environmental problems. It is usually necessary to consider levels of complexity above and below the main level of interest: 'each level of complexity finds its explanations of mechanism in the levels below, and its significance in the levels above.

Complexity

Complexity increases with the number of components conforming a system, however, there are other factors of great importance. Systems are classified into three:

1. simple systems of small-numbers,
2. simple systems of large-numbers, and
3. middle-number systems.

The first ones can be adequately handled using differential equations. The second ones can be handled by replacing the individual entities by their mean using a statistical approach. However, when complexity increases none of these two approaches is useful: the parts are too few or too different to reliably average them, but too many to represent each one with an equation. Middle-number systems require the viewpoint provided by the general systems theory.

Systems Analysis: Systems analysis can be defined as the application of the scientific methods to problems involving complex systems. It is a body of theory and techniques for studying, describing and making predictions about complex systems, which often is characterized by use of advanced mathematical and statistical procedures by using computers. The goal of systems analysis in fisheries management is to promote good decision making in practical situations. Systems analysis is the formalized study of any system, or of the general properties of systems.

What is a model?

A model is an abstraction of reality. It is the formal description of the essential elements of a problem. A model for systems analysis can be thought as a formal description of the system of interest. The description can be physical, mathematical or verbal. A **mathematical model** is a set of equations, which describes the inter-relationships among system components. By solving these equations we can mimic, or simulate the dynamic (time varying) behavior of the system.

A very general definition of model, from the viewpoint of its relation to reality is: “An object ‘A’ is a model of an object ‘B’ for an observer ‘C’, if the observer can use ‘A’ to answer questions that interest him about ‘B’. This definition can be applied equally well to mathematical models, scale models, and simulators (machines like flight simulators). Implicit in the definition is the fact that there is a goal in modelling (given by questions that interest the observer). As reality is complex, every model is a partial projection of the reality on a domain of interest, taking into account the state of knowledge of the modeller.

A model is an incomplete representation of reality

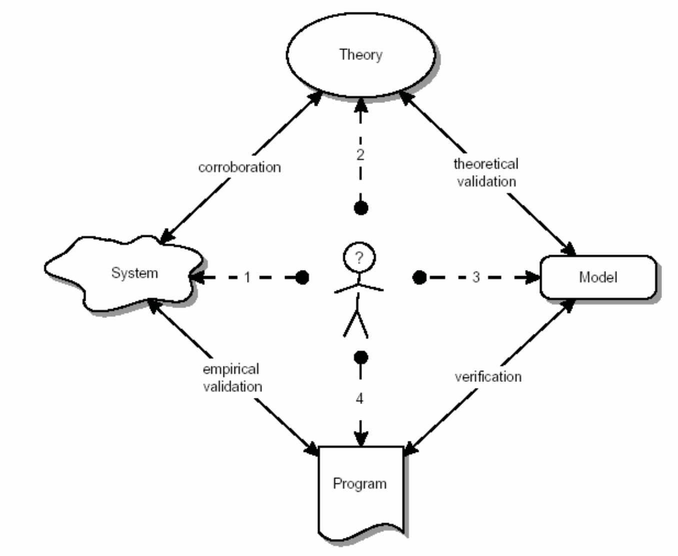
- because we have a goal and strive for simplicity
- because we are ignorant and brain capacity has limits

In systems analysis, a model is thought as a collection of variables and relations between them.

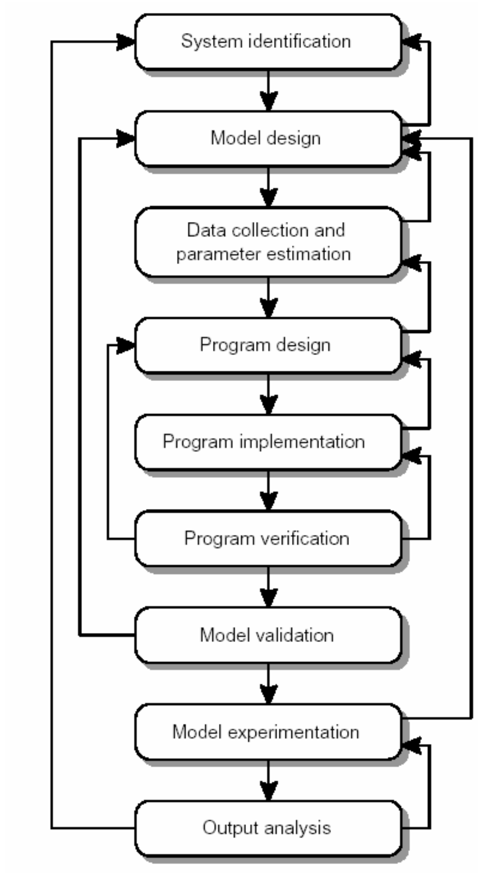
- ✍ A parametric model is a functional relationship, with the values of the parameters unspecified: it gives the structure of the model.
  For example: $y = f(x) = a \cdot x$, where a is a parameter.
- ✍ A mathematical model is a parametric model plus a set of values for the parameters.
  For example: $y = f(x) = 2.35\ x$, with $a = 2.35$.
- ✍ Simulation is to do experiments with a model.
- ✍ Experimental frame is the subset of all the experiments doable with the real system that can be reproduced with the model.
- ✍ Experimental condition is the set of conditions within an experimental frame, which defines a particular experiment.
- ✍ The specification of an experiment consists in the specification of an experimental frame, plus a parametric model, plus a set of values for the parameters.

Modelling as a mental activity

1. system identification
2. system representation
3. model design
4. model coding



Life cycle of a model



The boundaries of a model: System identification consists in defining the boundaries of the system to be modelled.

Patterns (of behaviour, in time)

- ✍ Linear growth
- ✍ Linear decay
- ✍ Exponential growth
- ✍ Exponential decay
- ✍ S-shaped growth
- ✍ Overshoot
- ✍ Overshoot and collapse
- ✍ Oscillation

Steps in modeling

1. Draw a graph of how an important variable changes with time.
   This is the "reference mode".
2. List policies that might improve the performance of the system.
3. Think about key variables and their interconnections.
4. Always remember that we should leave out unimportant factors and keep the important ones.

Classification of models: Models can be classified in different ways

<u>Physical model Vs Abstract model</u>: Physical models are physical replicas of the objects under study on a reduced scale. Ex.: A marine aquarium is a physical model of a marine ecosystem. A scaled down architectural model used to help us visualize floor plans and space relationships is a physical model of multi-floored building. Abstract models use symbols rather than physical devices to represent the system. The symbols can be written languages, verbal description or a thought process. A mathematical model is a special type of abstract model written in the language of mathematics. Since mathematical notation is more specific than language, mathematical models are less ambiguous than word models.

<u>Dynamic model Vs Static model</u>: A dynamic model describes a time varying relationship. Simulation models are dynamic so also some regression models involving time as independent variable. A static model describes a set of relationships that do not change with time. Regression models with out time component are static.

<u>Empirical model Vs Mechanistic model</u>: Empirical models are developed primarily to describe and summarize a set of relationships, without regard for appropriate representation of processes or mechanisms that actually are operating in the real system. The goal of empirical models is prediction and not explanation. Another term used for empirical models is correlative model. Ex.: A model predicting metabolic rates of an animal solely as a function of body size, surplus production models in fish stock assessment. Mechanistic models, otherwise known as explanatory models, are developed primarily to represent internal dynamics of the system of interest. Here the goal is explanation through representation of the casual mechanisms underlying system behavior. A model representing metabolic rate of an animal as a function of body size, level of activity, environmental temperature, wind and length of exposure to ambient conditions is an example of mechanistic model.

<u>Deterministic model Vs Stochastic model</u>: A model is deterministic if it contains no random variable. Predictions using deterministic models under a set of conditions are always exactly the same. Ex: Model developed relating energy requirements of an

individual (in kcal/day) to ambient temperature (in ?C) given by $y = 100 - 2x$ is a deterministic model. A model is stochastic if it contains one or more random variables. Stochastic model predictions under a specified set of conditions are not always exactly the same, because random variables within the model can take different values each time the model is solved. Choice between deterministic and stochastic models depends on the specific objectives of modeling. Deterministic models are easier to build, as it does not require specification of the distributions for the random variables. Prediction for a given situation need to be made only once for deterministic models where as stochastic model predictions must be repeated sufficiently to obtain the average response for a given situation.

Analytical model Vs Simulation model: Models that can be solved in closed form mathematically are analytical models. A general solution that is applicable to all situations can be obtained for analytical models. Regression models, differential equation models, models of standard theoretical statistical distributions etc. are analytical models. The analytical model for population growth given by the formula $N_t = N_0 e^{rt}$ is an analytical model. Here N_t is the population size at time t, N_0 is the initial population size and r is the intrinsic rate of population increase. Models for which a general analytical solution is not possible must be solved numerically using a specified set of arithmetic operations, for each particular situation the model can represent. Such models are known as simulation models. Most of the ecological models are simulation models. In ecological modeling, the choice between analytical model and simulation model is based on whether we sacrifice ecological realism to obtain analytical model or sacrifice mathematical power to include more ecological realism.

Different Phases of Systems Analysis: There are several aspects of problem definition that always should be considered before application of systems approach.

I. Conceptual Model Formulation
   Model formulation consists of a) Bounding the system of interest b) Categorizing components within the system c) Identifying relationships between components and d) Formally representing the conceptual model.
II. Quantitative Specification of the Model
   Quantitative specification of the model is composed of a) Choosing the general quantitative structure for the model b) Choosing functional forms of model equations c) Choosing the basic time unit for simulations and parameterizing model equations and d) Formally presenting and computer coding model equations and executing the baseline simulation.
III. Model Validation: The components of model validation are a) Examining capability of the model to address the problem of interest b) Examining reasonableness of model structure and individual model mechanisms c) Examining qualitative reasonableness of overall model behavior d) Examining quantitative correspondence between overall model behavior and real system behavior and e) Sensitivity analysis of the model
IV. Model Use: Model use is the final part of system analysis and it involves a) Identifying management policies or environmental situations to be evaluated and representing them in the model b) Developing the experimental design for simulations c) Analyzing and interpreting simulation results and d) Further examining selected types of management policies or environmental situations.