The core of GIScience
a process-based approach

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Chapter 7

Models and modelling

Rolf de By
Menno-Jan Kraak
Otto Huisman

Introduction

The working environment of the geoscientist should offer functions to deal with the diversity of the data at any moment is what can be called geodata processing. It should encourage connections between the different phases of problem solving and facilitate the linking of concepts, data and models. Geodata processing comprises the steps of exploration, synthesis, analysis, evaluation and presentation, although not necessarily in that sequential order (Figure 7.1). In theory, with a particular geo-problem in mind, one starts with the exploration of available data, which leads to a research hypothesis or a conceptual idea.

Synthesis, the next step, leads to theories or models that will be subject to analytical processes. The results of these will be evaluated and followed up with the presentation of the final result, indicating the confidence one has in the result, so that one might may appropriate decisions. In practice, geodata processing might not involve all of these steps or even consist of several iterations.

Modelling is commonly carried out to solve real-world problems. A modelling activity must therefore begin with a clearly-stated purpose. Sometimes, is more useful to discuss the modelling process itself rather than the precise meaning of the model. A model can be defined as a simplified representation of some aspects of a real system. By creating a model, we move from the real world into an abstract world of concepts, mathematical constructs, spatial queries and techniques for delivering solutions. We re-enter the real world with the solution in hand, at which stage that solution is translated into a useful answer to the real-world problem. Models—as simplified representations—come in many different “flavours”.

7.1 What is a model?

The word “model” can be read as a verb, which means “to describe” or “to represent”, but it can also be used as a noun. In Van Dale’s Dutch dictionary (Van Dale’s Groot Woordenboek der Nederlandse Taal) a “model” is defined as “a schematization of

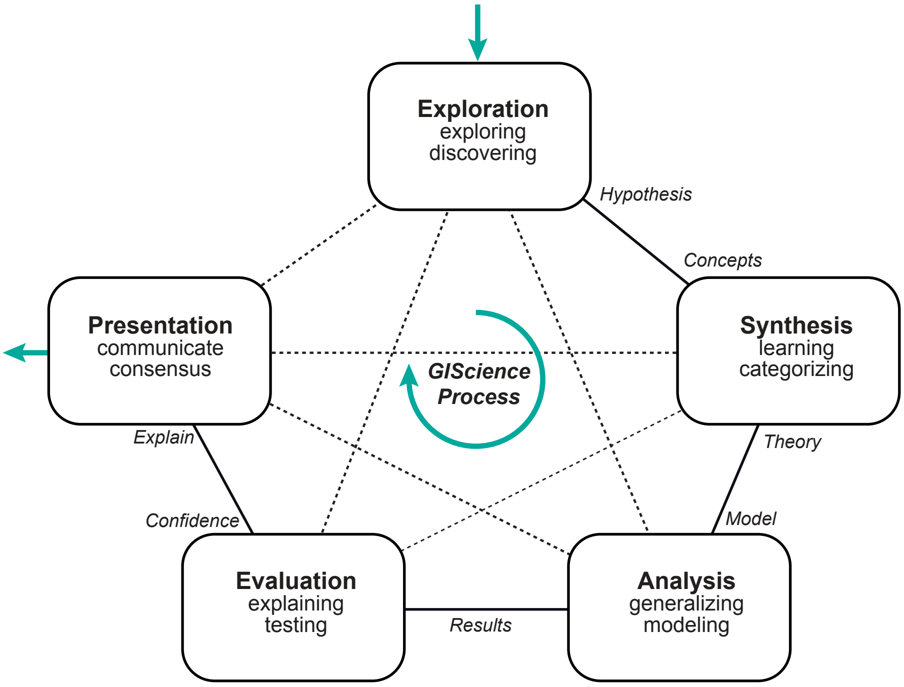

Figure 7.1
Geodata processing comprises the steps of exploration, synthesis, analysis, evaluation, and presentation. Between each of these steps, certain actions—via a combination of visual an algorithmic approaches—are executed.

model

reality with operational potentials”. This points to the intimate relationship between the type and degree of schematization and the objectives for the call on the operational potentials. Meijer (1984) stresses this call on potentials as follows: “A model is an object or concept that is used to represent something else. It is reality scaled down and converted to a form we can comprehend.”

Here we will use the following definition of a model: “A model is a manageable, comprehensible and schematic representation of a piece of reality”. This definition can be explained as follows:

- “reality”: as scientists we usually wish to model reality and not a hypothetical system. Reality is, however, vast and infinitely complex. Describing (modelling) reality in all its facets and complexity is therefore impossible.
- “a piece of reality”: we focus on a limited domain in time and space, incorporating only specific aspects, focusing on perhaps only one or just a few objectives. We represent a number of phenomena that we can observe in reality, usually to enable study, administration, computation and/or simulation.
- “schematic representation”: reality is only considered from a specific point of view. This implies imperfections and limited accuracy (e.g. projection of the Earth onto a map).
- “representation”: an infinite number of projections, thus different representations of the same piece of reality are possible, resulting in an equal number of modelling possibilities.
- “a comprehensible representation”: a model serves a specific goal. A model is used as an aid to diagnose, analyse or predict the behaviour of the modelled system. The user is central in this. The user needs to be able to understand the

functioning of the model itself, as well as how the model and the real world differ.

- "a manageable representation": for the same reason as the previous item, the model needs to be manageable. It should give users the results they need to be able to answer their questions, to find solutions to their problems. Users need to be able to "play" with the model (change variables, experiment, evaluate, etc.).

So far, we have not discussed types of models, which may be mathematical or statistical models, conceptual models, spatial models, scale models, to mention a few. Before we look closer at model types, we first need to discuss the various functions of models.

7.2 Function and use of models

Models can be used to serve various objectives or functions, for example to better understand a spatial phenomenon, to represent a phenomenon, to measure or calculate a distance, or to set up plans for a disaster response unit within a city.

7.2.1 Insight versus prediction

Models may be used to gain a better understanding of the system that they represent, i.e. the structure of real-world systems and the way they work. Different elements of the model and their interrelations may be manipulated by changing variables, attributes, equations and parameters. As such, it is possible to experiment using a model instead of with the real-world system (even if that would at all be possible, simulating flooding under real-world conditions is usually not possible or feasible). These kind of models are used abundantly in science.

Models can also be used to predict the future behaviour of a system, with or without interventions. It is important is to ensure that the model represents future behaviour accurately enough (usually based on knowledge about current behaviour or historical trends). Simple extrapolations may not always be desirable, as results obtained from the past are no guarantee for future behaviour!

Scenarios based on simulations may be used to sketch possible future developments. A possible future is constructed based on a well-described initial situation. Over time, several changes occur or are introduced, thereby changing the predictions. Scenarios are particularly useful when used in comparison with other scenarios (starting from the same initial situation). Scenario models and model predictions are typically used in policy studies.

7.2.2 Measuring versus calculating

In many applications it is not sufficient to only know what is happening (qualitative). Usually we also need to know to what extent something is happening (quantitative). Such quantification is common in, for example, engineering, finance and economics, environmental sciences and physical geography. Quantitative measurements can be obtained by direct measurement (from prototypes, scale models or analogue models) or by calculation. In the latter case, scientists need quantitative information to answer questions such as "What traffic volumes are to be expected on this new bridge?" or "How large is this deforested area?" In the first question, the object or system has not yet been realized if the bridge is not already built and operating, so only a predictive model can help. If such a model is a mathematical model, then the different variables (quantities) that are considered to be important and their interrelationships are expressed in equations (formulas), after which mathematical operations can be executed (to predict, to control, to optimize). In the second question, the deforestation has already taken place and direct measurement is possible (e.g. through a NDVI).

7.3 Modelling

It is not possible for we human beings to know or comprehend reality completely. Nevertheless we create images of reality that differ both between individuals and over time. These images often consist of a simplified reproduction of the processes in or around us, the relations between these processes, and so on. In creating an image, it is impossible to involve every aspect of a process simultaneously. Fortunately, we do not need to do so: it is sufficient to consider only a few aspects at a time. Moreover, we usually create an image as a schematic reproduction. Which aspects we involve and to what extent we use schematic reproductions depends on, for example, our activities, knowledge, interests, disposition and the required precision.

Models are constructed to answer questions concerning parts of reality. This restricts their use to only certain aspects of the modelled phenomena. Moreover, models are limited in time and space. A model will, therefore, never be universal. A third important characteristic of models is that they are—even within the limits of the chosen aspect(s)—only an approximation; anything not primarily important will be left out. Remember, models are a schematic representation of a piece of reality.

These characteristics make clear the limited validity of models. If many factors are involved, it is especially difficult to indicate the validity—within which errors will be reduced to an acceptable amount—in advance. The implementation of models therefore involves uncertainty, so validation is needed, i.e. testing the model to see if it has a sufficient sense of reality.

uncertainty

The schematic representation of a model implies that for a certain question, there is no one correct model. On the contrary, a multitude of models could be relevant for the question concerned. Depending on the required precision and the time and means available, we may want to use a simple model or a complicated one, representing more aspects or more detail. The question “which model do we need to solve which problem?” is therefore inappropriate since many models may do the job.

In the process of developing a model, several concepts, terms and variables that may not be literally part of reality are introduced. Those concepts and variables represent certain idealized aspects of this reality and are called modelled variables.

Applying a model following recognized (mathematical) rules generates model outcomes. For these outcomes, the same rules apply as for the modelled variables: they are valid *within* the model and should not be seen as characteristics of the modelled reality. This is similar to the rules and outcomes of a board game: they are limited to the game and do not apply to the real world.

Because each model is based on a schematic representation of reality, or some part of it, the outcomes may be unrealistic when compared to the reality the model wants to represent. This requires a critical evaluation of models and their outcomes, even if a model has been previously validated; it is not as if its implications automatically involve the same situation. Those who implement a model therefore need sufficient understanding and knowledge of the processes being modelled in order to be able to judge the model. Unfortunately, this is not always the case. The easy accessibility of computer programs has given modelling capabilities to people who may not be aware of the limits of their knowledge or the validity of the model outcomes.

7.4 General characteristics of models

A few general characteristics apply to all models. When building a model the following questions could be useful for exploring the model's general specifications/attributes:

- what is the problem to be modelled? (e.g. inaccessibility of a city centre);
- what are the important phenomena? (e.g. road congestion, urban land use);
- what is the spatial domain? (e.g. a built-up area of a city);
- what is the temporal domain? (e.g. morning peak-hour);
- what is the desired accuracy? Depending on the type of use, more- or less-detailed modelling (e.g in terms of spatial resolution) may be needed.

For operational use of the model, other questions are also relevant, such as:

- who is going to use the model (the problem owner?); and
- what resources are available for building the model (time, money).

Randers [96] distinguished nine general characteristics of models, where the objective of the study determines the importance of each of the characteristics. These general characteristics are:

- insight-generating capacity: the model increases insight into the system and its image;
- descriptive realism: system and model structure are similar;
- model reproduction ability: model reproduces typical system behaviour;
- transparency: the model is useable and understandable, also by non-experts;
- relevance: according to experts, the model provides meaningful solutions to the problem;
- ease of enrichment: the model can easily be adapted;
- fertility: the model stimulates generation of new ideas, new experiments, new policy;
- formal correspondence with data: the model reproduces known observations accurately;
- point predictive ability: the model makes good predictions.

Most models, particularly those used in GI Science, try to increase knowledge of and insight into the observed behaviour of systems or to estimate the effect of changes (choice options) on their behaviour.

7.5 How to build a model

The modelling process consists of three distinct phases: model development, model operationalization, and model application, in that order.

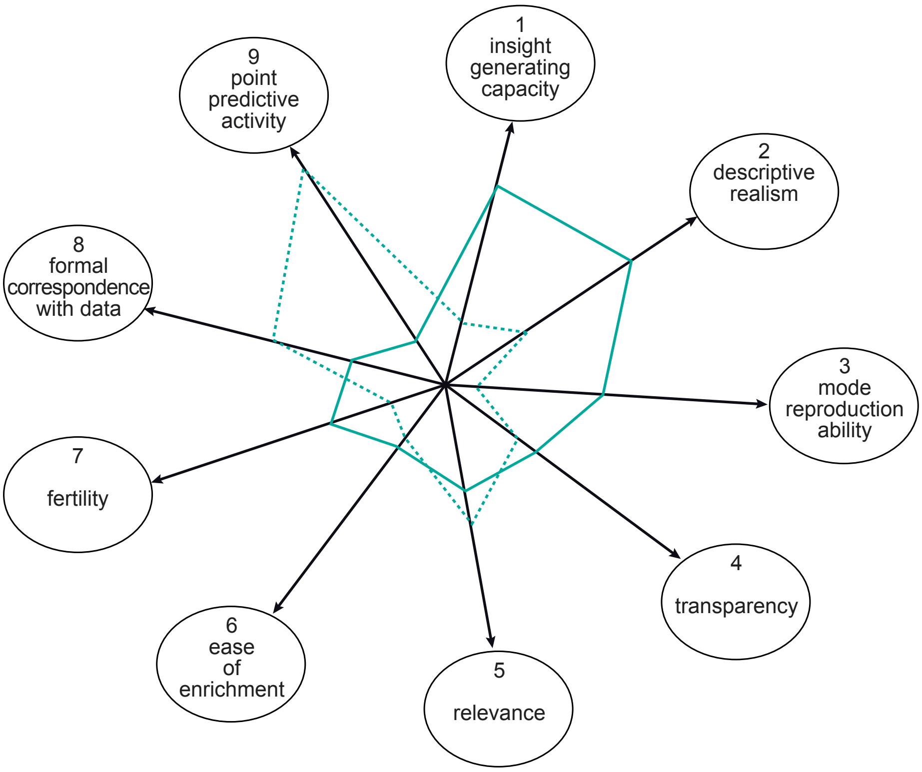

Figure 7.2
A spider diagram relating model characteristics according to Randers [96] and the study objective. Broken lines indicate predictive types of models; solid lines indicate descriptive types of models.

Model development The following 10 steps (see Figure 7.3) may lead to the proper (mathematical) development of a model:

- problem analysis;
- conceptual modelling;
- model formulation;
- conceptual validation;
- model implementation;
- verification;
- calibration;
- validation;
- analysis; and
- model use, communication and evaluation.

Operationalizing In the second phase, modelling concept and modelling are implemented, perhaps using commercially-available software. Functional and technical design, software validation, user-interface development, etc., are addressed. The compilation of a manual with a detailed description of the underlying model, including metadata, belongs in the operationalization process.

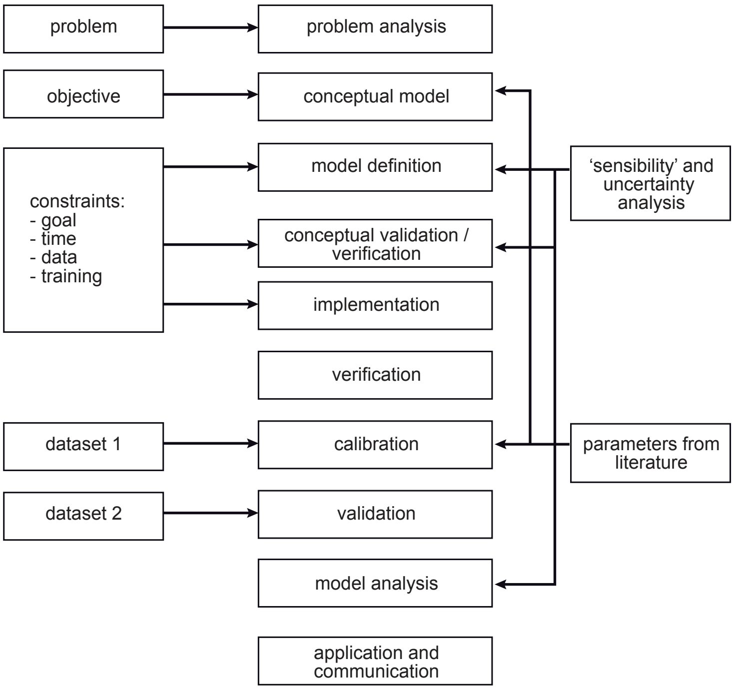

Figure 7.3
A summary of the modelling process.

Application In the third phase, the model is used for calculations, simulations or making predictions within the context of the problem that had to be solved in the first place.

In total, the modelling process therefore entails the following activities: problem analysis (including area demarcation; schematic representation of processes; choice of modelling type and strategy; data collection, model development; and model calibration and verification. Sensitivity and uncertainty analysis, model presentation and visualization, and, finally, model communication may also be part of this process.

7.6 Modelling in GISs

In the GIS environment, the most familiar model is a map. A map is a miniature representation of a part of the real world. Databases are another important class of models. A database contains (spatial) data and also provides various functions for operating on that data. The collection of stored data represents a real-world phenomena, so it also is a model. Digital models (such as a database or GISs) have advantages over paper models (e.g. analogue maps), being more flexible and therefore more adaptable for the purpose at hand. Digital models may also allow animations and simulations.

"Data modelling" is the common name for the design effort of structuring a database. It involves the identification of the kinds of data that the database will store and the relationships between them. Most maps and databases can be considered static models, representing a single state of affairs at a point in time. Dynamic models or process models, on the other hand, address developments or changes in the real world: changes in the past, in the present or at sometime in the future. Dynamic models are inherently more complicated than static models and usually require much more computation. Simulation models are an important class of dynamic models that allow the simulation of real-world processes.

GISs and application models We have already mentioned that real-world processes are often highly complex. Models are simplified abstractions of reality representing or describing its most important elements and their interactions. Modelling and GISs are connected, since a GIS is itself a tool for modelling a part of "the real world". The solution to a problem usually depends on a number of parameters. Since these parameters are often interrelated, their interaction is made more precise in an application model. Such a model describes as faithfully as possible how the relevant phenomena (in our case, often geographic) behave, doing so in terms of the parameters. Application models varying in nature. GIS applications for famine-relief programmes, for instance, are different from earthquake-risk assessment applications, though both use GISs to derive a solution. Many kinds of application models exist and they can usually be classified in various ways. Here we identify five ways of classifying the characteristics of GIS-based application models (compare with the model of Randers in Figure 7.2):

- the purpose of the model;
- the methodology underlying the model;
- the scale at which the model works;
- its dimensionality, i.e. whether the model includes spatial, temporal or spatial and temporal dimensions;
- its implementation logic, i.e. the extent to which the model uses existing knowledge about the implementation context.

These classifications express different ways for classifying model characteristics. Any application model has characteristics that can be described according to the above categories. Each of these is briefly discussed here.

Purpose of the model The purpose of a model refers to whether the model is descriptive, prescriptive or predictive in nature. Descriptive models attempt to answer the "what is" question. Prescriptive models answer the "what should be" question by determining the best solution from a given set of conditions. Models for planning and site selection are prescriptive in that they quantify environmental, economic and social factors to determine "best" or optimal locations. Predictive models focus upon the "what is likely to be" questions and predict outcomes based upon a set of input conditions. Examples of predictive models include forecasting models, such as those attempting to predict landslides or sea level rise.

Methodology underlying the model The underlying methodology of a model refers to its operational components. Stochastic models use probabilistic functions to represent random or semi-random behaviour of phenomena. By contrast, deterministic models are based upon a well-defined cause–effect relationship. Examples of deterministic models include hydrological flow and pollution models, where the "effect" can often be described by numerical methods and differential equations. Rule-based models address processes by using local (spatial) rules. Cellular Automata (CA), for example, are often used for systems that are generally not well understood, but for which local processes are well known. For example, to model the direction of spread of a fire over several time-steps, the characteristics of neighbouring cells (such as wind direction and vegetation type) in a raster-based CA model might be used. Agent-based models (ABMs) model movement and development of multiple interacting agents (which might represent individuals), often using sets of decision rules about what the agent can and cannot do. Complex agent-based models have been developed to understand aspects of travel behaviour and crowd interactions, incorporating also stochastic components.

Scale Scale refers to whether a model component is individual or aggregate in nature. It refers to the "level" at which the model operates. Individual model components are based on individual entities, such as in agent-based models, whereas aggregate models deal with "grouped" data, such as population census and socio-economic data. Models may operate on data at the level of a city block (for example, using population census data for particular social groups), at a regional level or even a global one.

Dimensionality Dimensionality refers to the static or dynamic character of a model and to its spatial or non-spatial nature. Static vs. dynamic modelling has been discussed in Subsection 7.6. Models operating in a geographically defined space are explicitly spatial, whereas models without spatial reference are aspatial.

Implementation logic Implementation logic refers to how the model uses existing theory or knowledge to create new knowledge. Deductive approaches use knowledge of the overall situation in order to predict outcome conditions. This includes models that have a formalized set of criteria, often with known weightings for the inputs, and for which existing algorithms are used to derive outcomes. Inductive approaches, on the other hand, are less straightforward, in that they try to generalize (often based upon samples of a specific data set) in order to derive more general models. While an inductive approach is useful if we do not know the general conditions or rules that apply to a specific domain, it is typically a trial and error approach that requires empirical testing to determine the parameters of each input variable. Most GISs have a limited range of tools for modelling. For complex models, or functions that are not natively supported in a GIS, external software environments are frequently used. In some cases, GISs and models can be fully integrated (known as embedded coupling) or linked through their data and interface (known as tight coupling). If neither is possible, the external model might run independently of a GIS; the model output should be exported into the GIS for further analysis and visualization. This is known as loose coupling.