Supporting the Construction of Qualitative Knowledge models

Bessa Machado, V.

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1.1 Modelling as means of problem-solving

In many fields, real world phenomena are studied indirectly by means of models. In this context, a model is an abstract representation of an object or a system including those features thought to be important for the intended analysis.

Using models has the advantage of making knowledge explicit. Building models requires the use and manipulation of knowledge, not just observation and repetition. Formulating, testing, and repairing models stimulates the apprehension of scientific reasoning skills. Moreover, being able to reflect, discuss, and exchanging models with peers and teachers induces a better and deeper understanding of science (e.g. [91, 26]). This not only improves the retention of relevant knowledge but also its application and transfer. Hence modelling is becoming increasingly more important as means to learn and educate [17].

To date the use of mathematics has been prevalent in most modelling activities. In those cases, important features are represented numerically and the relations between them are expressed by means of equations or inequalities. However, mathematical models have no way of explicitly representing objects, typical situations, mechanisms of change, causal explanations, conditions for things to start and to finish. As such, mathematical models do not capture explicit knowledge on how to perform an analysis or how to interpret simulation results [71]. Consequently they are limited to helping to understand the mechanisms underlying the behaviour of a system.

Qualitative Reasoning, in contrast, provides means for representing and understanding reasoning by use of conceptual knowledge. Its formalisms provide ontological primitives capable of describing a conceptual analysis of system behaviour, including the important notion of causality [35, 43]. Due this emphasis on capturing means for explaining how a system behaves, qualitative models are sometimes referred to as 'articulate knowledge models' [44, 19].

However, the use of qualitative reasoning engines in classroom settings is difficult because user-friendly tools are not available. Building a complete model, and inspecting its simulation results, require programming skills in LISP or PROLOG. In this thesis we address this problem. The goal of this research is the deployment of an easy to use Qualitative Reasoning modelling workbench that provides the full potential of a qualitative reasoning engine and can be used to support learning about behaviour of physical systems.
1.2 Conceptual Modelling using Qualitative Reasoning

Research on Qualitative Reasoning concerns the development of representation and reasoning mechanisms that enable a computer program to reason about the behaviour of physical systems without precise quantitative information as needed by conventional analysis techniques [117]. Two observations were the motivation for using Qualitative Reasoning. Firstly, people can reason and then draw conclusions about the physical world without using mathematical equations. Secondly, in order to understand and interpret quantitative formulae and simulation results, scientists and engineers often use qualitative knowledge.

Qualitative physics began with the investigation of de Kleer on how qualitative and quantitative knowledge interacted in solving simple textbook mechanics problems [34]. Automatically generating explanations in the context of quantitative simulation-based learning environments was one of the important motivations for the research carried out during the early days (e.g. [21, 57]). In the meantime the area has grown significantly, with many contributions on problem solving with incomplete information. This has made the technology relevant to many real-world problems. It has proven to be cost effective, reliable and efficient, as a means of analysing the behaviour of systems for which detailed numerical information is missing [18]. It has for instance been applied successfully to problems in the automotive industry [90, 94], to aeronautics [120], thermodynamics [46], and ecology [93, 96, 97]. To date, qualitative models have mainly been developed by AI researchers and knowledge engineers.

Qualitative models have characteristics that make them particularly suited to address specific learning activities. For instance, when teaching to solve physics problems, teachers emphasise the need for learners to first understand the (problem) situation. Before trying to apply equations, learners should build a conceptual model of the initial-state, the end-state, and the possible transition trajectories between the two [80]. In fact, it is considered naive (beginners behaviour) if learners jump to 'applying formulae' without making a proper analysis of the problem situation (e.g. [40]). Expert problem solvers excel because they spend a significant amount of time on making a conceptual model before using equations. Analysing (problem) situations is close to the idea of making an envisionment, that is, a mental simulation of what happens, or may happen [35].

Qualitative models are also relevant in specific domains where domain experts try to uncover the causal dependencies that govern the behaviour of a system. After understanding the causal dependencies the experts may try to apply the mathematical formulae that are appropriate for the system. In fact, the causal model helps them to find the appropriate equations. Experts often do not even bother about the equations. Instead, developing a conceptual model is a goal in itself, that is: discovering the physical constituents of the system, identifying the relevant quantities, and understanding how these interact in determining the behaviour of the system. Qualitative models are well suited to help domain experts in articulating and formalising their insights (e.g. [95]). If we think of how this kind of knowledge can be communicated to (new) trainees in the field, qualitative models are again crucial.
1.4 Support in articulating knowledge

Building qualitative models is a difficult task [100] and providing users with a graphical model building workbench may not be sufficient for effective use. Moreover, the workbench that we envision will be domain independent and usable in different areas of science teaching. It is therefore most likely that additional support is needed. However, as the workbench still needs to be developed, the specific support requirements are currently unknown. Determining and addressing the support requirements, to have users effectively use the workbench that we envision, is therefore an integral part of the research presented in this thesis.

1.5 Research Goals

Constructing simulation models is a difficult and time consuming task, this is particularly true for qualitative models. Tools and methods have to be developed to support the modelling process [100]. Following from this, in this PhD research, the main objective we are pursuing is to develop a model building method and a corresponding model building environment that supports users in the construction of qualitative models. The method specifies how models should be built and how users can be supported during the model building process. The model building environment is a kind of workbench that facilitates the different facets of the model building process. This goal can be further specified in the following research questions:

- What are the tasks involved in qualitative model building?
- How will the model building environment, as well as the status and results of the model building process, be visualised on the computer screen?
- What kind of support should be provided for users while constructing a model?

To answer the research questions an incremental approach is taken. This approach consist of two major steps. Within each step a fully operational prototype software system plays an important role. The first prototype is largely based on a rational task analysis and principles for visualisation. It should address the requirements following from that as much as possible. The system is then evaluated with users, testing usability and support needs. The second prototype should be an improvement of the first, based on the requirements following from the experiment with the users. The second prototype is then also evaluated to determine the degree in which the research goals are satisfied and what future improvements may still be needed.

1.6 Outline of the Thesis

The subsequent chapters are described briefly below.
1.3 Graphical Representations in Problem Solving

Many researchers have emphasised the important role that graphical representations play in problem solving [122, 30]. Anderson [5], for instance, proposes that conceptual knowledge is based on the meaning of a representation. Diagrams, graphs, and pictures are a few typical examples of graphical representations. They are used in many cognitive tasks such as problem-solving, reasoning, and decision-making [104, 11, 73, 106]. When used in an educational context for learners to construct and articulate ideas such representations are often referred to as external representations.

It is commonly agreed between researchers that external representations help in reducing the internal processing load needed to solve a problem. Various representations may hold equivalent information but they may differ in terms of how much effort is needed in order to communicate their contents. Take for instance a diagram and a textual description of the same information. It is often the case that a graphical representation is a more effective means of transmitting an idea than its equivalent textual representation (e.g. [70]). Take for example a diagrammatic depiction of a subway route map. Many people are able to read subway route maps. Given the destination station it is usually easy to find a route that will take you there, even in large cities. The diagram shows the pattern of linkages explicitly; it does not need to be remembered. Compare this to the implicit memory load given a textual description.

Bertin [11] proposed that graphical representations can be used for communicating a simple message, or providing support in information-processing tasks. The cognitive benefit of using external representations, and in particular graphical ones (such as the subway map example), is the ability to shift internal cognitive processes and information to external ones, in most cases changing the nature of information-processing tasks [73, 123, 99]. This characteristic is denominated Computational off-loading by [99]. The benefit is established through Re-representation and Graphical constraining. Re-representation refers to the process of looking into the information from a different perspective or abstraction level, thereby abstracting from information which is irrelevant for the task at hand. Graphical constraining refers to the restriction on possible interpretations of the information, and in doing so guiding the viewer to a certain conclusion. Computer tools can be used advantageously to promote new ways of thinking by providing support to the users in externally representing their ideas, test their understanding and receive feedback on it.

In our research we are interested in designing such a computer tool. We want to develop a model building workbench that supports users in building qualitative models using a common external representation. The software environment should help users in expressing their qualitative, conceptual knowledge as a means to learn to understand phenomena. Providing a common representation will enable users to discuss and reflect on their models, and by doing so construct meaning and understanding. It is well known that externalising thoughts through annotation, tracing and other methods can greatly assist in problem-solving (e.g. [30]).
Chapter 2 discusses the design of tools that can support the process of building qualitative models and simulations. In the first part of the chapter, we present an analysis of model ingredients that can be used in the construction of qualitative models as well as the subtasks involved in this building process. The second part of the chapter is devoted to the design of a graphical user interface that supports the model building process. This involves discussing guidelines for visualising model ingredients and subsequently applying these guidelines to the design of specific tools, as well as taking decisions concerning manipulations and basic support within these tools.

Chapter 3 presents an experiment carried out to evaluate the design implemented within our first system for building qualitative models (HOMER). The chapter is divided into two main areas. The first four sections deal with the experimental procedure and the presentation of the implemented system. The second part, presents the experiment results and their analysis. The analysis is structured around three main areas, a) validating the task analysis as presented in Chapter 2, b) assessing the tool’s usability in supporting the model building process c) identifying problems and/or misconceptions users encountered when building simulation models with the tool.

Chapter 4 introduces an approach to support the model building process. It starts with a short review of learning environments that turn out to have important similarities with HOMER. These systems are analysed and compared to HOMER, particularly with respect to the problems encountered by the subjects while constructing their models (as described in Chapter 3). This results in a set of lessons learned: a set of guidelines on how to design a help system as part of an environment for supporting the entire model building process.

Chapter 5 brings together the ideas presented in earlier chapters on how a model building system should be designed in order to effectively support the model building process. We present a model building tool called MOBUM that implements these ideas. Subsequently, we describe and discuss the principal design decisions of MOBUM.

Chapter 6 documents two studies on model building environments. In the first study we examine the manner in which subjects use MOBUM to solve model building tasks. Analyses of the subjects’ (novices and experts) actions, verbal communications and interviews were conducted in order to pinpoint to what extent MOBUM is effective in supporting modelling tasks and how easy it is to use. The second study compared the use of MOBUM and HOMER by novices in performing modelling tasks. The study addresses questions of usability, preferences of the participants of one system over the other, the functionality of the help engine (its usefulness for successful completion of tasks) and the perspectives of the participants on the use of such systems.

Chapter 7 summarises the results and presents the conclusions and contributions of the research reported. We discuss the scope of the application of MOBUM and indicate avenues for further research development.