Qualitative Futures

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Abstract

This paper considers where the QR field might be in twenty years time, outlining five areas where developments in model-based systems in general, and qualitative reasoning in particular might have a significant effect on what can be achieved. The paper also examines where the QR community should concentrate its efforts in order to improve the usefulness of the technology.

Introduction

Model-based systems and qualitative reasoning (MBS&QR) as a visible sub-field of Artificial Intelligence can be traced back some twenty years to the publication of the seminal collection of papers in the field [Bobrow], although there was of course earlier work in this area [de Kleer ; Brown et al.].

The 1984 collection of papers showcased early research, much of which has been developed over the years, and resulted in realistic demonstrations of the technology. The next section of the paper gives a summary of where we are in being able to build systems using MBS&QR.

This paper looks forward for the next twenty years, considering what MBS&QR will be recognized for in twenty years time. It selects five areas where MBS&QR can make a significant difference, and details the nature of the technological challenge in that area.

None of these challenges can be met completely with the technology that we have developed so far. For this reason, the paper also explores the areas where further research in MBS&QR is needed in order to fulfill the vision of model-based applications given here.

State of the Art

There has been a great deal of work in MBS&QR over the past twenty years, and much of it has seen its earliest publication in the pages of the previous 18 annual QR workshops, or on the diagnostic side, in the 15 annual DX workshops.

This section gives an idea of the variety of applications and domains in which model-based reasoning is currently being used. It can be seen that this is already a technology with a wide range of applicability. It also provides a great deal of value for those who apply it.

The kinds of systems being built with MBS&QR now are:

Fault detection by model based prediction: numeric and non-numeric

If one knows what values the system parameters should have, then one can detect faults by seeing if the system is producing these values or not. But for many systems, the behavior of the components and sub-systems is not well enough known to be used for a numerical simulation. In this case, qualitative reasoning and simulation can be used to produce a description of the overall expected system behavior, thus enabling fault detection [Travé-Massuyès and Milne; Benezera et al.; Benazera and Travé-Massuyès].

System simulation before the real system is built, such as satellite design, or virtual prototyping of vehicles

The developers want to understand what the system will be like, but it won't be physically constructed for some time. Complex products involving discrete and process sub systems are very difficult to model with traditional simulation systems, but the qualitative nature of the behavior of the system can be determined with qualitative simulation [Benazera and Travé-Massuyès; Ward and Price].

Process understanding and monitoring

Operational plants don't run complex numerical simulations all the time, but the operators still need to know if the plant is reacting as it should, for example, temperatures increasing and decreasing when they should be. In addition, the numerical simulation creates a complex set of numbers when the user really wants to understand that the key system parameters are increasing or decreasing. Qualitative reasoning, on the other hand, can provide an appropriate level of reasoning [Adam and Grant; Trelease and Park].

Explanation of numerical simulations

Numerical simulators produce a battery of numbers, but not the easy to understand description of system behavior

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the user is looking for. [Forbus and Falkenheiner]. Qualitative reasoning can extract the system's qualitative behaviors from the simulation output, enabling a comprehensible explanation for the user [Price].

Compositional Model based diagnosis and state tracking
By linking together a collection of component descriptions, diagnosis can be performed on the whole system, and the state of the system can be tracked over time. This is much faster and requires less man effort that traditional manual design and analysis approaches [Dvorak and Kuipers; Struss and Price].

Model based systems provide many opportunities for re-usability
Once the model based description of a component is created, it can be used in many system configurations. Model based systems build system descriptions from the composition of many sub models, the key to this reusability [Struss and Price].

Variants problem
Current approaches have a high cost of developing diagnostics as the sub-systems change. These variants are desirable, but too expensive to support. A model based system automatically generating the diagnosis makes this practical and hence opens up a whole new area of commercial opportunity. The automotive area is a prime example. [Struss and Price]

FMEA generated from the design description and component models
Automatically generating the Failure Modes and Effect Analysis from the design description of an automobile's electrical system saves considerable man effort and is more accurate. Automated sneak analysis has identified problems not previously detected, for example. Model based FMEA is now a standard module offered by design company Mentor Graphics [Struss and Price].

QR models in the educational context
Qualitative reasoning can be used to simulate systems for students so that they can understand the errors they have made and how a system should function [Bredeweg and Forbus 96].

QR to help decision making under uncertainty
In marketing, the knowledge is imprecise and often unknown. For example, evaluation of credit risk of companies and classifying the profiles of consumers call for qualitative descriptors. QR can be used where numerical approaches are not applicable [Flores et al.].

Visions for the Future

This section presents a range of challenging potential applications which are more advanced than we are capable of achieving at present, and which depend on model-based reasoning for successful execution. The presentation of these as "twenty year visions" is somewhat arbitrary. The visions highlighted in the section are:

- The Science-bot: automated education
- Virtual vehicles: from conception to recycling
- Understanding and managing complex natural systems
- Interpretation of 4D medical data
- Robust autonomous problem solvers in the face of uncertain situations

The Science-bot: automated education

Scenario:
A science-bot is an interactive agent that is knowledgeable about a set of topics in science. Each science-bot is specialized in its own area of expertise. It will have considerable amounts of domain knowledge and be able to assist learners in helping them to acquire knowledge, understanding and awareness. Science-bots will recognize and know the informational needs of their learners and users and adjust the communicative interaction so it is appropriate to the specific user. Additionally, they will have their own teaching and communication goals depending on the circumstances in which they have been placed. Specifically science-bots will be able to discuss topics from multiple perspectives, explain phenomena and criticize ideas and thoughts presented to them.

Tutoring and training was one of the earliest applications of model-based reasoning, e.g. [Brown et al.; Hollan et al.; Wenger]. Presently there are several types of model-based tools available for use in educational settings. Examples of these typically take the form of model-building environments (using the idea of 'learning by knowledge articulation') and interactive simulations, and they deal with a variety of issues. For surveys of qualitative reasoning and education, see for example [Bredeweg and Forbus; Forbus; Bredeweg and Winkels].

MBS&QR technology is of great importance for developing, strengthening and further improving education and training on topics dealing with systems and their behaviors. Educators and learners need the means to capture and share conceptual knowledge. That is, means to formally represent (and automate reasoning with) knowledge that is qualitative, incomplete, fuzzy and uncertain, and in communicative interactions frequently expressed verbally and diagrammatically. Not being able to sufficiently represent this knowledge in a computer-processable format, preserving its unique characteristic, hampers the sharing and communication of insights and theoretical developments. This is particularly a problem in education and training situations. QR technology can provide computer-based facilities to represent and reason with this kind of conceptual knowledge. However, MBS&QR technology is not well known to a wider audience and there are currently not many ready to use products and tools available to exploit the capabilities of this technology. As result, the full potential of qualitative models as a key component of tutoring systems and interactive learning environments is still to be established.

We envision that the following products can and should be developed in order to address the need for educational software dealing with learning about systems and their behavior. *Interactive articulation devices* are model building environments that allow learners to articulate knowledge (conceptual models) and by doing so learn about a domain. Learning by modeling using traditional approaches has been shown to be effective for enhancing student understanding, but is often hampered by the mathematical complexity of knowledge representations and the lack of means to represent causal knowledge. QR has the capacity to overcome these hurdles. Based on MBS&QR technology, tools can be developed that will allow diagrammatic sketching of ideas and conceptual knowledge and, have this automatically transformed into simulations. In order to be effective, such environments should also have the means to criticize models and simulations, and help learners with de-bugging them.

The concept of *autonomous science-bots* further advances the idea of individualized support, by the building of resources of previously defined models / model parts and coaching. Science-bots focus on knowledge transfer related to institution-defined goals (where the institution might be a university or school etc.). *Autonomous training-bots* are a special class of science-bots. They operate side-by-side with workers (for instance, in factories or business oriented environments) providing online help and also support for these workers with performing their tasks. MBS&QR technology can provide to the basis for developing such a tools.

The virtual vehicle: from conception to recycling

Scenario:

Vehicle manufacturers and their suppliers face increasingly serious challenges. The complexity and sophistication of vehicles is growing, and so it is becoming harder to predict interactions between vehicle systems, especially when failures occur. Legal regulations and the demand for safety also impose strong requirements on the detection and identification of faults and the prevention of their effects on the environment or dangerous situations for passengers and other people. Finally, customer satisfaction is important in order to remain competitive, and means that the manufacturer must minimize break-downs and reduce maintenance time and the number of misdiagnoses.

The cost of meeting these challenges for a new vehicle model has increased over time, and is becoming overwhelming, both in terms of manpower and elapsed time. In response, vehicle manufacturers have gradually moved towards virtual prototyping and automated analysis. Virtual prototyping involves using software to construct a model of a system, and testing the model works correctly, thereby reducing the need for actual prototyping. This process can be significantly improved by automated analysis, having software performing analysis on the models – for example, failure modes and effects analysis – so that the engineers need to spend less time analyzing the system.

The ideal end point of this activity would be the virtual vehicle – a model of the complete vehicle that can be developed and used throughout the lifetime of the vehicle. When it is first decided to make a new vehicle, then the requirements can be used to build a functional model of what the vehicle will be required to do. This might allow automatic specification of much of the complex equipment in the vehicle. As the design is fleshed out by the engineers, either stipulating physical components or specifying the aesthetic aspects of the vehicle (which will constrain design choices), then the extra information should be incorporated into the model of the vehicle from databases of component models. When enough information becomes available, it will be possible to perform model-based tasks of the type described earlier – failure modes and effects analysis, system simulation, diagnosability analysis, production of diagnostics, generation of control software. As variants of the new vehicle design are produced, all this work can be repeated with much less effort, reusing all information that can be used from the original model. When the vehicle is finally disposed of, the virtual vehicle can be used to plan disassembly and efficient disposal of materials.

This is far from trivial. At present, many of the models being created are useful for one task, at one point in the vehicle's lifecycle, Model-based reasoning is a vital technology for the virtual vehicle. The use of compositional models makes it possible to automate the repeated reasoning on a design which is necessary for this kind of work. In particular, qualitative reasoning has an important contribution in enabling early analysis before all information is available, and also in focusing numerical reasoning to obtain more specific results. One issue that will become more important is the ability to reason as effectively as possible about a system where different subsystems are specified with different degrees of detail – perhaps only a qualitative model exists for one subsystem, a functional model for several others while one or two subsystems can provide detailed numerical models. Combining these different levels of information is not possible at present, but will become vital if the virtual vehicle is to be realized.

Understanding and managing complex natural systems

Scenario:

We wish to understand the mechanisms and rates for complex natural systems where a good deal of data is available, but good models are not. Traditional machine learning techniques can produce models of such systems, but they do not provide models where the mechanisms in the domain are visible and capable of explanation. For example, we might be interested in the germination dynamics of the spores of fungal pathogens, such as the oospores of Plasmopara viticola, in response to both endogenous factors, either metabolic (e.g. the influence of the calcium ion) or genetic, and to exogenous factors due to the climate (e.g water availability) and environment on the germination process. A deep comprehension of such complex interactions is essential for a rational and optimized treatment planning of plants with a consequent benefit for the health of both consumers and operators, and for the impact on the ecosystem. The available pathophysiological knowledge on the endogenous mechanisms at work is highly incomplete and qualitative whereas the exogenous factors can be completely and quantitatively known (under laboratory conditions). Moreover, the mechanisms involved may occur at different time scales. There is the need for the development of proper QR-based modeling methods that are capable of dealing with different levels of knowledge, and even more important, with different time scales.

Models of the dynamics of natural systems offer potential benefits to the deep comprehension of the system under study as well as to the performance of specific tasks. The dynamics of such systems result from complex interacting mechanisms, and are very often regulated by both endogenous and exogenous factors. Unfortunately, the available knowledge of the underlying mechanisms is very often highly incomplete, and identifying mechanisms with quantitative methods is a challenging prospect. This makes the modeling problem quite hard to solve, and even insolvable when, as can occur for natural systems, the available observational data set is inadequate.

QR methods properly integrated with quantitative methods could overcome the identification problems outlined above. An example of a successful application of a QR-based hybrid method to solve serious identification problems deals with the identification of the intracellular Thiamine (vitamin B1) kinetics in intestinal tissue [Bellazzi et al. 2001]. Understanding this system is quite important, as Thiamine is one of the basic micronutrients present in food and essential for health; it participates in carbohydrate metabolism, in the central and peripheral nerve cell function, and in the myocardial function, and its deficiency causes beriberi with peripheral neurologic, cerebral and cardiovascular manifestations.

Interpretation of 4D medical data

Scenario:

One of the most stimulating application domains where QR can fruitfully support traditional quantitative techniques in the investigation and comprehension of complex phenomena is Electrocardiology. In present clinical practice, information about the heart electrical activity is routinely gathered through Electrocardiographs (ECG), which record electrical potential from just nine sites on the body surface. However, thanks to the latest technological advances, body surface potential maps are becoming available, as well as epicardial maps obtained non-invasively from body surface data through mathematical model-based reconstruction methods. This 3D data is gathered over time, giving a 4D data set. Electrocardiographic maps can capture a number of electrical conduction pathologies (arrythmias, Wolf Parkinson White syndrome, just to cite a few) that can be missed by ECG analysis, but the interpretation of such maps requires skills that are possessed by very few experts.

An important role in the process of defining an interpretative rationale for electrocardio-graphic maps can be played by QR methodologies for spatial/temporal reasoning that could (i) support the expert in identifying salient features in the map, and (ii) achieve the long term goal of automating map interpretation to be used in a clinical context. QR approaches based on spatial aggregation [Bailey-Kellogg and Zhao] may be used to identify patterns and salient features in epicardial activation isochronal maps [Ironi and Tentoni 2003a]. In this kind of map, the time at which each point starts activating, derived from the electrical data of a whole heart beat, is visualized by means of isocurves. A lot of information about the excitation wavefront structure and propagation is summarized in a single such map, since isocurves represent subsequent snapshots of the travelling wavefront.

Breakthrough location, high and low velocity pathways, conduction block regions, for example, are salient features that characterize the heart electrical activity: they visually correspond to specific geometric patterns to be identified in the map, such as minima location, maximum and minimum elongation directions in the isocurve shapes.

Spatial aggregation approaches, designed for the interpretation of numeric fields that are spatially represented, and capable of identifying global patterns and capturing structural information about the underlying events exist in the literature. But, such methods just consider 2D geometrical domains that can be discretized by a uniform mesh. But, given the complexity of the geometry of the heart (3D and non uniform meshes), such methods are not applicable to the interpretation of cardiac maps, and therefore there is the need for the development of methods capable of dealing with 3D complex geometries over time.

Besides helping medical research in the important phase of the definition of interpretative rationales through models and their simulation, QR methods can lead to the automated interpretation of numerical fields in specific medical domains, and therefore to the realization of tools that could eventually enter clinical practice.

Robust autonomous problem solvers in the face of uncertain situations

Scenario 1:

Satellite systems need to make decisions no matter what information is available.

A satellite system has constructed a plan of how to achieve its goals. However, the key infrared sensor is not responding. Using its Model Based System, a new plan is constructed. It then uses a qualitative simulation to verify that the plan meets the goals. The simulation also generates expectations which can be used to monitor the execution of the plan to detect problems. The satellite executes its plan, matching sensory data to measurements and completes the mission.

Scenario 2:
An autonomous planetary rover, comparing its limited sensory data to a prediction of the sensor readings detects an inconsistency as it moves down the side of a shallow crater. It uses a Model Based System composed of models of each component to determine that a component has failed. Even if a sensor is lost; it needs to plan what it will do to complete the mission. It then reconfigures itself and re-plans the mission with its new system structure. Its sensory data now matches the predictions of its Model Based System and it reaches the crater floor to continue its explorations.

These are two situations where autonomous decision making is needed by a system. There are others outside of the planetary exploration domain - robots in hostile environments, or building maintenance systems where a human supervisor is not continually present.

Autonomy requires a global perception - state identification - action loop, which is essential to provide the system with adaptable behavior to face unknown events. Fault Detection Identification and Reconfiguration (FDIR) involves a set of functions, which are obviously crucial to adaptability.

Model-based diagnosis (MBD) techniques would benefit the overall spacecraft and constellation design process. These tools indeed provide an integrated development framework able to produce easily the equivalent to the currently used on-board FDI systems and providing substantial additional benefits from the development step to the operation step:

- the FDI design will be easier to build, reusable and more generic when based on MBD,
- MBD enables a global and unified management of the equipment and functional levels,
- the models can provide support for validation,
- MBD should lead to a decreased level of false alarms by making maximum use of redundancies and numerous non telemeasured on-board observations,
- MBD should be able to handle automatically more situations than the current FDI systems, avoiding the satellite or constellation to transit to "safe mode" and consequently increasing availability.

Techniques for autonomy will offer new possibilities for the development of spacecraft missions by helping engineers automatically produce a large part of the ground and on-board software as well as a great help for the hardware specification and the design of the most useful on-board sensors and telemeasures. Space engineers should be able to produce more complex constellations and spacecrafts for difficult exploration or critical missions.

Technological Priorities

The previous section has presented a number of targets for the application of MBS&QR. This section will consider what improvements to available MBS&QR technology are needed in order to achieve those targets.

One issue which will not be addressed any further in this section is the one of cross-discipline research. While we believe that MBS&QR have a key contribution to make to the realization of the visions in the previous section, *they are not MBS&QR problems per se.* The Science-bot, for example, will also need advances in analogical reasoning and user modeling, in order to be able to work in the way that is outlined.

However, for all of the visions described, we consider that MBS&QR are central to the efficient production of workable systems, and this section classifies the needed technological improvements as either *vital* or *important.*

Vital technologies

These technologies are needed in order for MBS&QR to achieve widespread successes, as opposed to the targeted breakthroughs that have been achieved so far.

More powerful modeling formalisms / frameworks
Many of the processes that we are modeling evolve over time, happen in a particular space, and are impossible to specify completely as not all relevant parameters can be determined (giving rise to uncertainty). In addition, lack of precise data makes it impossible to describe the system quantitatively. Many real-world systems are very complex; and while the exact nature of the complexity varies from system to system, the contributors to degree of complexity are: non-linearity, order, dimensionality, degree of coupling and non-determinism. Further research is needed in more powerful modeling languages, in coupling models at varying levels of abstraction, and in developing spaces of models from which an appropriate model can be selected.

QR methods using more sophisticated mathematics
In many cases, methods from model-based systems and qualitative reasoning build upon existing mathematical methods from calculus (e.g. differential equations), algebra (equations, functions and sets), and logic. The basic methods are geared towards the area of model-based systems and qualitative reasoning: (1) by restricting the domains and co-domains of functions to be discrete,

possibly ordered, instead of being continuous, and the results are then still consistent with the underlying axioms, (2) by adding task-specific problem solving methods, such as methods for diagnosis, which are able to act on particular representations in a particular fashion. There are many mathematical methods which are restricted in their practical usefulness because qualitative versions of them are as yet not available.

Integration of models from different domains
In many situations it is necessary to consider phenomena with different natures in order to reason about a system. In the field of continuous industrial processes, many devices, such as pumps, comprise phenomena related to hydraulics and mechanics. In the automotive industry cars comprises different inter-related subsystems such as hydraulic, electric and electronic.

Integration of models is an open problem, and further research on this topic is closely related with research on ontologies. Some work has been done using domain independent ways of modeling such as bond graphs, although that work has not been as successful as might have been expected. One of the reasons may be that bond graphs are well suited to simulation, but less adapted for the other tasks performed by model based systems.

It may be that a combination of appropriate methodologies for individual domains, plus the development of standards in an integrated manner for interfacing models in different domains may finesse this problem, but at present it is still an open problem.

Important technologies

These technologies, while important, tend to be needed for a few fields of application, rather than vital to the whole usage of QR. If you are working in that particular field, then the kind of advances discussed here may be vital to you, but they are less important than the first category to the widespread application of MBS&QR.

Models of software
The modeling of the action and influence of software is an issue for almost any advanced man-made device or system. For example, in the automotive domain, electronic control units (ECUs) containing many thousand of lines of software control the state of vehicle subsystems, and often perform monitoring, diagnosis and reconfiguration of systems. It is necessary to incorporate the actions performed by software in models, in order to understand the state of the device, and perform device-specific tasks. Similar issues occur in other domains, such as model-based reasoning about process control systems.

Models to represent system specifications and requirements
One of the major advantages of model-based reasoning for problem-solving is that it can consider many more possible scenarios than a human could. One of the key concepts for qualitative model-based systems is that of an "envisionment". An envisionment is a map of all of the possible states that a given system can reach, and how the system moves from one state to another. It is generated by exhaustive simulation from all states to see what other states can be reached.

For systems where safe operation is an issue, an envisionment provides important indications of the possibility of reaching unsafe states or situations. In other types of application, it might be possible to specify "interesting" states of a different sort. In order to identify interesting/unsafe states, two things are needed:

Descriptions of what is interesting. This can involve capturing descriptions of the way in which the system should work, and might include issues of complex dynamic time varying and continuous systems, dealt with elsewhere in this section.

Abstraction of state descriptions. It must be possible to abstract the results of an envisionment so that they can be compared with the descriptions of interesting states.

This area is in its infancy, but we would expect it to make a significant contribution to system safety and reliability as it becomes better developed.

Hybrid modeling
Different modeling techniques allow the capture of different aspects of the same phenomenon. Hence, in order to include in one model different aspects of the same phenomenon or even different phenomena, you need to integrate models from different sources.

Examples:

- Pure qualitative models allow one to focus on significant behaviors, while pure numerical models allow one to detail each one of these behaviors or even to solve ambiguities related to the qualitative reasoning.
- Causal models and models based on quantitative differential equations provide two different views of the same phenomenon.

Few systems are capable of combining different modeling approaches. Currently, the main research effort is devoted to produce and to use semi-qualitative models.

In the future, model-based systems need to be able to combine different types of models to solve a given problem. The target to be achieved might be the kind of reasoning displayed by human experts, who seem able to combine information from different types of models seamlessly, and to combine information from partial models of each type.

Multi-level modeling
It is necessary to combine models at different levels of abstraction to solve a particular problem, usually to cope with complexity.

Examples:

- In the food industry, the evaporation station can be modeled, at least, at three different levels: simple mass balances (product conservation), detailed balances (mass and energy conservation) and detailed dynamical model for control purposes.
- In the computer industry, a computer can be viewed at different levels, from high-level functional components to chips.

Currently, there are different theoretical proposals: automated handling of diagnosis hypotheses, multiple models considering available time for diagnosis, multiple levels of abstraction regarding the quality of the diagnosis. However, there is almost no application on industrial systems capable of handling models at different levels of abstraction, because there is no systematic way to share results from different models within the same task.

A real applicable methodology needs to be proposed to change smoothly from one level to another, exploiting results from different levels.

Eventually the reasoning system should be able to select the adequate level of abstraction automatically, and to switch from one to another as required.

Combining qualitative and functional models
Much qualitative research has concentrated solely on reasoning about the structure and behavior of systems. For many applications, it is necessary to abstract the results in terms of the function or teleology of the system. That implies being able to represent teleological knowledge, to reason about it, and to map behavioral knowledge to it. This has been done for systems with fairly static behavior. That work needs to be extended to cover complex, dynamic time varying functions.

Automated model generation from simulation models
The exploitation of model-based systems in industry will greatly depend on the (additional) modeling efforts they require. This lead us to the attempt of reducing these efforts by automated conversion of existing simulation models into abstract models suited for model-based problem solvers.

Simulation models of a system are often created for control purposes. However, for diagnosis, for example, specific properties are needed from a model:
There is a need for methodologies that ensure that the models are built correctly in the first place for use in other tasks that simulation, and techniques that make the process of converting those models to ones appropriate for diagnosis and other tasks is a painless process.

Derivation of qualitative models from requirements
During the design process, the correct operation of a system is often described at a high level, perhaps in terms of state charts. Such information is often very useful when performing model-based reasoning. Better methods are needed of integrating it into the construction of model-based systems.

Automated modeling
Automated model building and model transformation needs continued theoretical work and more effective and efficient algorithms [Ironi and Tentoni 2003b]. This is emphasized by application requirements. Much of the expected gain depends on fast and economic creation of models from a library. Since different tasks may require models at different levels of abstraction, there is a tension between the desired compositionality and generality (and, hence reusability) of models and the necessity of task-oriented models. QR needs to develop techniques to generate task-oriented models from generic ones.

This also touches upon a more general goal, namely integrating QR results and techniques with standard engineering practice and tools. The lack of integration presents a major obstacle to transferring QR technologies into industrial practice. Deriving qualitative models from numerical ones that have been developed, for instance, in the phase of design verification, is of high practical importance. However, it may require changes in current modeling practice towards modular, component-oriented models. The need to blend in with current practice also applies to other domains, such as medicine, economy, biology and ecology.

Model-based system identification
Model building is a difficult and time consuming process. A much more efficient alternative to building models by hand would be to learn models from observed data. This is still a very difficult machine learning challenge for complex domains. Qualitative reasoning can help with this in two ways.

Learning qualitative models. In domains such as some areas of biology, where the underlying models may not be known, it will be possible to learn qualitative models from data. Early research in this area indicates that it is more useful to build qualitative models rather than numerical models at this stage, in order to facilitate understanding by domain experts.

Deriving quantitative models from qualitative models. In domains where qualitative models are known, but are not executable, qualitative reasoning provides graphical ways of building executable models, and makes clear the assumptions behind the models, enabling domain experts to compare their models on a like-for-like basis. Where models are known and data is available, it should make it possible to develop accurate numerical models with known assumptions and limitations [Bellazzi et al. 2000].

The main impact of these techniques may well be in science rather than in engineering, providing tools for scientists to understand the world better, and having a dramatic impact on the way that we carry out scientific research.

Conversion of qualitative models

One issue concerns the development of better engineered and easy-to-use *tools* that facilitate the exchange of results among researchers and make QR techniques available to potential users in other areas and application work. The field, so far, has developed a variety of theories, formalisms, and techniques with different degrees of generality and is still far from delivering a small set of uniform principles and systems. If the field can make progress on this, it will become easier to create and exchange *libraries* of reusable models.

A further issue for the commercial adoption of MBS&QR

Several researchers report that one barrier to the adoption of the technology has been that no tool is available to allow the (comparatively) simple construction and deployment of qualitative models of systems. Tools such as QSim [Kuipers] and QPE [Forbus 90] are too complex for many of the kinds of processes that people wish to implement when investigating the technology. VModel [Forbus et al.] is a much better example of the kind of tool that is needed, except that the level of modeling is too simple for many example systems. An extension of VModel to be able to reason about systems over time, plus an application programmers interface to allow users to build systems based on running the model, might be a valuable research tool with many potential users. The GARP-related tools [Bredeweg and Forbus] are also making steps in the right direction.

Conclusions

Model-based and qualitative reasoning has had a productive and useful childhood. As it enters its third decade, both the challenges for the technology and the promise it holds are greater than ever. The visions in this paper are intended as encouragements to researchers in the field. We are engaged in an enterprise with immense potential benefits. In order to succeed, we need both people who will drive work on the difficult applications described here, addressing problems of integration with other technologies and commercial issues, and researchers who will solve more of the basic issues that need to be resolved in order to build these visionary systems.

Acknowledgements

This paper is based on work carried out by the MONET European Network of Excellence in Model-based and Qualitative Reasoning. The authors listed are those involved in production of the final technological roadmap produced by the network. However, we also acknowledge the contribution of other members of the network, and of those who contributed through the "futures" session at QR04 in Evanston, Illinois.

References

[Adam and Grant] G. Adam, E. Grant, Qualitative modelling of lime-mash flow processes and measurements, in Advances in Systems Science: Measurements, Circuits and Control, Mastorakis and Pecorelli-Peres (eds), p60-63, WSES Press, 2001.

[Bailey-Kellogg and Zhao] C. Bailey-Kellogg and F. Zhao. Qualitative spatial reasoning: extracting and reasoning with spatial aggregates. AI Magazine special issue on Qualitative Reasoning, pp47-60, vol. 24(4), Winter 2003.

[Bellazzi et al. 2000] R. Bellazzi, R. Guglielmann, L. Ironi: How to improve fuzzy-neural system modeling by means of qualitative simulation, IEEE Trans. on Neural Networks, 11, 1, (2000), 249-253.

[Bellazzi et al. 2001] R. Bellazzi, R. Guglielmann, L. Ironi, C. Patrini: A hybrid input-output approach to model metabolic systems: An application to intracellular thiamine kinetics, Journal of Biomedical Informatics, 34(4), (2001), 221-248.

[Benazera and Travé-Massuyès] E. Benazera, L. Travé-Massuyès, The consistency approach to the on-line prediction of hybrid system configurations, *IFAC Conference on Analysis and Design of Hybrid Systems (ADHS'03)*, Saint-Malo (France), 16-18 June 2003, 6p.

[Benezera et al.] E. Benezera, L. Travé-Massuyès, P. Dague, State tracking of uncertain hybrid concurrent systems. DX02, pp.106-114, 2002.

[Bobrow] D. Bobrow (ed), special issue on Qualitative Reasoning About Physical Systems, Artificial Intelligence 24, 1984.

[Bredeweg and Forbus] B. Bredeweg and K. Forbus, Qualitative modeling in education, AI Magazine special issue on Qualitative Reasoning, pp35-46, vol. 24(4), Winter 2003.

[Bredeweg and Winkels] B. Bredeweg, R. Winkels, 1998. Qualitative Models in Interactive Learning Environments: An Introduction. *Interactive Learning Environments*, Volume 5, Number 1–2, pages 1–18.

[Brown et al.] J. S. Brown, R. Burton, J. de Kleer. Pedagogical and Knowledge Engineering Techniques in SOPHIE I, II and III, in "Intelligent Tutoring Systems", D. Sleeman and J. S. Brown (eds), pp227-282, Academic Press, New York, 1982.

[de Kleer] J. de Kleer, Multiple Representations of Knowledge in a Mechanics Problem-solver, in Proceedings IJCAI-77, pp299-304, Morgan Kaufmann, 1977.

[Dvorak and Kuipers] D. Dvorak, B. Kuipers, Process monitoring and diagnosis: A model-based approach, IEEE Expert 6(3), p. 67-74, 1991.

[Flores et al.] J. J. Flores, B. Flores, F. Gonzalez, Qualitative/quantitative financial analysis, In procs. 15th Intl Workshop on Qualitative Reasoning, QR01, 2001.

[Forbus 90] K. Forbus, The Qualitative Process Engine, in Readings in Qualitative Reasoning about Physical Systems, edited D. Weld and J. de Kleer, pp220-235, Morgan Kaufmann, 1990.

[Forbus 96] K. Forbus, 1996. Qualitative Reasoning. In The Computer Science and Engineering Handbook, ed. A. B. Tucker, 715–733. Boca Raton, Fla.: CRC.

[Forbus et al.] K. Forbus, K. Carney, R. Harris, B. Sherin,. A qualitative modeling environment for middle-school students: A progress report. In procs. 15th Intl Workshop on Qualitative Reasoning, QR01, pages 65-72, 2001.

[Forbus and Falkenheiner] K. Forbus, B. Falkenheiner, Compositional modeling: finding the right model for the job, Artificial Intelligence, vol 51, pp95-143, 1991.

[Hollan et al.] J. D. Hollan, E. L. Hutchins, L. Weitzman,. STEAMER: An interactive inspectable, simulation based training systems. AI Magazine, volume 5, pages 15-27, 1984.

[Ironi and Tentoni 2003a] L. Ironi, S. Tentoni: Towards automated electrocardiac map interpretation: an intelligent contouring tool based on Spatial Aggregation, Lecture Notes in Computer Science, 2810, (2003), 397-408.

[Ironi and Tentoni 2003b] Ironi, S. Tentoni: A model-based approach to the assessment of physicochemical properties of drug delivery materials, Computers & Chemical Engineering, 27, 6, (2003), 803-812.

[Kuipers] B. J. Kuipers, Qualitative Simulation, Artificial Intelligence 29, pp289-338, 1986.

[Price] C. J. Price, Function Directed Electrical Design Analysis, *Artificial Intelligence in Engineering* 12(4), pp 445-456, 1998.

[Struss and Price] P. Struss and C. J. Price, Model-based systems in the automotive industry, AI Magazine special issue on Qualitative Reasoning, pp17-34, vol. 24(4), Winter 2003.

[Travé-Massuyès and Milne] L. Travé-Massuyès, R. Milne, TIGER^{TM}: Gas turbines condition monitoring using qualitative model based diagnosis, IEEE *Expert Intelligent Systems & Applications* 12(3), p. 21-31, 1997.

[Trelease and Park] R. Trelease, J. Park, Qualitative process modeling of cell-cell-pathogen interactions in the immune system, Computer Methods and Programs in Biomedicine., Vol. 51, pages: 171-181, 1996.

[Ward and Price] D. Ward and C. J. Price, System functional safety through automated electrical design analysis, *SAE 2001 Transactions, Journal of Passenger Cars, Section 7 - vol 110: Electronic and electrical systems*, pp341-347, 2001

[Wenger] E. Wenger, Artificial Intelligence and Tutoring Systems: Computational and Cognitive Approaches to the Communication of Knowledge. Morgan Kaufmann Publishers Inc., San Francisco, CA, 1987