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1 Introduction

1.1 Purpose of this Document

Model-based Systems (MBS) and Qualitative Reasoning (QR) technology is of great importance for developing, strengthening and further improving education and training on topics dealing with systems and their behaviours. It is well known that an essential part of modern education and training involves the comprehension of systems and their behaviours. That is, being able to distinguish a system from the environment in which it operates, to identify the parts that it is made of, and to predict or explain its behaviours. The latter concerning the overall system behaviour, how that potentially interacts with the behaviour of the environment, as well as how the system's behaviour originates from the individual behaviours of each of the parts[1] that it consists of.

Although, not all education and training involves reasoning about systems (for example, language teaching does not seem to fall within such a paradigm), many matters in educational settings, work situations and every day life do. MBS&QR technology is important because it provides a computer-based means to capture and communicate knowledge and insights that overcome limitations of currently used technology, such as numerical-based simulations. However, MBS&QR technology is not well known to a wider audience and there are not many ready to use products and tools available to exploit the capabilities of this technology. This is an undesired situation as a great possibility for improvement is potentially left unexploited.

In this roadmap we depict the current situation concerning MBS&QR technology for education and training. We then envision how this should change in the future, and how we may accomplish that vision, following the needs and desires from the field.

2 Drivers

Throughout Europe (and Globally) educational institutions are facing a decline in the numbers of students who are choosing to take a science education in science. Many factors may be contributing to this fall in popularity, but the perceived complexity of the subject has a great part to play in this trend. If this trend is to be addressed (and reversed) there is a need to address the perceived complexity of the subject matter and to design teaching methodologies that respond to the ways particular learners develop knowledge. All of this has to be achieved with the limited teaching resources that are currently available to most institutions. Project-oriented learning is one tool that has the potential to be very successfully used to assist with this issue; this could be coupled with on the job training to develop systems and methods of learning that are applicable to all subjects and all learners.

2.1.1 Educational Institutions

Education in the sciences is declining due to fewer students choosing to study it and also due to the perceived complexity of the subject. This situation could be ameliorated by the use of interactive simulations which can make education more interesting and increase the involvement of students with the subject matter and thereby improve learning. Such simulations will also create a deeper and more profound understanding of the area, including the behaviour of complex systems. The current technology is not sufficient to fulfil this need. Improvements can be realised by having simulations based on QR technology that are knowledgeable about the subject matter, particularly facilitating explanation, interactive

[1] The terms 'Parts' does not only refer to components that constitute artefacts (*e.g.*, a switch being part of a device of some kind), but it also refer to entities or objects in general from which systems have grown (*e.g.*, a tree being part of a forest) or have been built (*e.g.*, a pole supporting some physical structure).

dialogues, computer-based diagrammatic reasoning and knowledge visualisation. An important innovation will be to introduce QR model building, as a means of learning, to earlier levels of education such as Junior and Secondary schools. Other innovations will be to use a formal and systematic qualitative vocabulary to assist learners in understanding mathematical models.

2.2 Modelling as a Means to Learn

Models and their use in the learning environment can radically improve the way in which learners develop knowledge. A wide variety of subjects demand an understanding of a large amount of data before an appreciation of the subject as a whole can be developed. Traditional learning techniques involve the transfer of this data to the student by methods such as text or lecturing and this wealth of information can appear daunting to many students. However, with modelling, all of the information is present but ‘hidden’ behind the interface with the learner. The learner uses the model, interacts with it, alters it and therefore can develop an overview of the subject in a manner (and timescale) that would not be possible with traditional learning techniques.

Once this overall impression and understanding has been developed the learner has acquired, possibly without their realisation, a mental web on which the more detailed information can rest. Data will be considerably easier for a learner to comprehend when they understand how the data is relevant to the subject and how it relates to other data. In other words, the data becomes a web of understanding not just a series of unrelated facts.

The models are, of course, not only of use to elementary learning. More advanced students can then use the same model to improve there knowledge by deeper interaction with the system. This can be taken further by interacting with the system to ‘build’ new models and to have the system check the learners ‘model’ and find any faults or issues. This action very clearly identifies both the level of the learners understanding and areas in which they require there understanding to be increased.

2.3 Distance-Learning

A problem in contemporary society, as noted by the European Commission, is the growing gap between people with access to knowledge and those without this access. An innovative method to reduce this gap is the use of distance learning technology, which provides opportunities for life-long learning in non-traditional settings for non-traditional learners. Currently the effectiveness of distance learning environments, compared to the classroom, is hampered by a lack of collaborative interactivity between and among students and teachers. Qualitative models facilitate causal reasoning and therefore learning because of their common sense ontology. Furthermore their easy transferral from off-line to on-line formats makes them especially conducive to distance learning via the world-wide web. Use of QR models for distance learning requires access points where students can interact with the model. Automatic explanation generation can be linked to automatic question generation so that students can be quizzed about system behaviour and hence learn the subject matter. All this can occur in a distance learning environment and QR software can be designed to automatically provide evaluations of student performance to the instructor.

Distance learning has the goal of increasing learning opportunities, but teacher resources remain critically limited. Innovation methods for efficient student evaluation need to be developed to counteract this conflict.

2.4 Life-long Learning

Life-long learning gives the opportunity for people to continue their study long after they pass the ‘usual’ educational age. People may find that they have time to study at other periods of their life, for reasons such as retirement and / or other work breaks, and the ability for them to learn should not be hampered by the temporal structure of ‘traditional’ educational institution.

Life-long learning gives the learner the ability to continue education as and when they can, be it a few hours a week or a year off from work commitments. The flexibility of model-based technologies means that people can learn in their own time and also that they can develop knowledge in any subject that the models support. The interaction of the learner and the learning system means that interaction with a ‘personal teacher’ is not required and this again adds flexibility.

2.5 Ecological awareness

Ecology is in a unique position relative to the other sciences because not only does everyone interact with their environment, but also they have the opportunity to be directly involved in important decisions regarding the environment. This opportunity stems from common ownership of ecological resources. Hence, increased public understanding of complex ecological processes (ecological awareness) will enhance opportunities for the public to make informed decisions.

2.6 Addressing Learner Information Delivery needs

Model-based reasoning for learning can have a dramatic impact on the way in which information is delivered; the systems can be designed to ensure easy to use modelling environments. Increasing the ease of use of any system will enable the information to be more readily delivered to the learner and this will have the subsequent effect of increasing the willingness of the learner to use the system and therefore increasing the efficiency of the learning process.

Support for a learner, regardless of subject area or learning reasons, will increase if the learner has direct interaction with a teacher. This teacher interaction is vital for student support, but it does not necessarily have to be face to face. Developments in web-based technologies, combined with model-based reasoning, can make it easier to interact with a teacher (or other students) and increase learning. This interaction can also be used as a part of the model, thus the knowledge of the teacher and the questions and issues that a learner has can be incorporated into the system. Therefore the learner is gaining the knowledge and experience of many professionals with years of experience without the requirement for them to be present.

This type of intelligent application makes it easy to develop professional training systems. The incorporation of personal knowledge into a model gives the ability for the experience of one person to be drawn upon by any number of end users at the same moment in time. This also means that one end user can draw on the experience of many experts by interacting with a single system.

2.7 Interactive Subject Matter Explanations

The construction and use of models in the learning environments makes it very simple to add in support for the learner. Additionally this means that the same set of data and the learning abilities of the system can also be used to support student assessment. The learner can have their knowledge tested by the system both in a formal set of tests or interactively as they work through the model. The system can continuously monitor their level of understanding and produce a record of the increase of their knowledge without the use of formal tests.

2.8 Immersing (Motivating) Interactive Simulations

The potential for ‘learning through play’ has been well developed for the education of the young, but it has applications to adult education as well. Motivating a learner will increase their willingness, and subsequently their ability, to learn and this can be achieved by getting the learner to immerse themselves in the learning process. With model-based systems the learner can be encouraged to move deeper into learning by interacting in the model construction process. Learners can couple this with simulations in order to test their model building ability and see how successful they have been.

2.9 Support Peer Collaboration / Learning

The Sixth Framework Programme is clearly focused at bringing technology to all. In an order to achieve this there needs to be a reduction in the gap between people with and without access to knowledge and learning. Educational QR systems have the capacity to assist by making expert knowledge and experience available to a wider audience, both on and off line. This will greatly aid the ability of communities to disseminate scientific results to the general public and do so in a manner which all can understand.

Community learning will also be increased by these actions; the easier (and cheaper) that systems can be made available to the public, and the greater the general comprehension of these systems, the more they will be put into use in the community. This increased uptake should also, itself, lead to further publicity of both the applications and their benefits, leading to yet further uptake.

2.10 Educate Stakeholders

Sustainable development is under stress following the development of worldwide economies and increasing global travel. This creates a demand to teach, inform and instruct a whole range of stakeholders in a range of ecological phenomena, their problems, impacts and solutions. The stakeholders include teachers, decision makers, politicians and managers in the areas of agriculture, industry, tourism, nature, and environmental and public sectors.

2.11 Eco-friendly Tourism

This is one of the growth areas of the tourism industry and is a potentially very valuable weapon in the fight against global ecological destruction. Simply stated, if an environmental niche can generate more capital income as a venue for eco-tourism than the value of its stripped natural assets then it is more likely that the stakeholders in that niche will seek to preserve rather than destroy it. However eco-tourism puts a tremendous strain on the areas that are earmarked for supplying this service, with the very tourists whose money is used to protect the area becoming the major eroding factor in the quality of the environment.

Little is know about the intricate balances and interrelationships that make up even the most simple of ecological niches and generating the amount of data required to assess this would require a huge computational cost. Applying knowledge / decision management systems to qualitative models can produce a system that can be used to model the effects of eco-tourism on an area or group of areas. Steps can then be taken to ensure that no (or little) long-term damage is done to the areas used for eco-tourism. This can be used to judge what numbers / levels / duration / etc of tourists could visit a site and cause minimal effect, or the models themselves can be used to judge how long and area could be 'visited' before it should be left to 'rest'. With a combination of ecological models and ecological decision support systems the negative effects of eco-tourism could be ameliorated and the positive enhanced.

2.12 Commercial Software and Education Materials

It is expected that some of the products mentioned in this document can be commercially exploited by the software industry and publishers. This includes model building environments, autonomous science-bots and training-bots, information systems, infrastructure, easy to use software packages to set up and support communities of practice, and teaching materials including textbooks and interactive CD-ROMs.

2.13 Enabling Communities of Practices

These are groups of users located in different places, connected via the Internet, working together on model-building and inspecting simulations in order to realise their goals. Such communities of practice may exist or come into being in many diverse areas, including schools, universities, industry and managers and other stakeholders such as tourism and ecology workers. To realise communities of practice the necessary infrastructure needs to be created, that supports collaborative distance learning (and working) in terms of model sharing and tools to communicate and discuss model content and features. It is expected that the products concerning interactive articulation devices and autonomous science-bots are important enablers for realising communities of practice.

2.14 Sustainable Development

Sustainable Development must now be the aim of all communities of the globe. But with very little information about the level of natural resources, let alone their consumption vs. replenishment rates, planning for an integrated approach to the management of our natural resources is very difficult. As already stated Qualitative Reasoning approaches fit very well with the requirements of ecological (i.e. in this instance natural resource) modelling. However, QR principles can actually be used to model a wide variety of situations and circumstances where data is incomplete or complex.

One important characteristic of this approach is that using the same technological basis for the models makes it considerably more likely that the resultant models could themselves be integrated to produce complex hybrid models. Factors such a population dynamics, ecological modelling can be brought together with other eco-models and used in an attempt to predict the effects of resource utilisation and distribution on Sustainable Development. This information can then be used to build models which facilitate the testing of different approaches to solving (or working towards solving) the issues that face the globe in a state of unsustainable development.

3 Products

Tutoring was one of the earliest applications of model-based reasoning (e.g. Brown et al. 1982), and there are several types of model-based tools that are presently available for use in educational systems:

Drawing and diagramming tools / QR-based modelling prototypes. These are tools where the user can interact with models of the system that they are trying to understand – they can be asked questions about it, and be given explanations to enhance their understanding.

Examples of such systems are those of Biswas et al. for complex problem solving and Forbus et al. for thermodynamics.

QR prototype learning environments. In these environments, the learner is given a task to perform. Assistance in the task is provided by a model-based system. In order to assist the learner, the learning environment must be able to use the model to diagnose problems with the learner's understanding, and be able to propose changes to their understanding which will improve their performance. Salles et al. provide an example of this in the ecological domain.

The rest of this section considers ways in which the use of models should broaden the types of intelligent tutoring systems that can be built over the next ten years.

3.1 Towards QR-based Curricula

By the end of the ten year period covered by this Roadmap, the goal of Educational MBS&QR is to develop curricula that are integrally based on QR models for a variety of science subjects. These curricula will include interactive models, practical exercises and assignments, and supporting multi-media material (e.g., text, video, audio). The goal is to enhance opportunities for student exploration and high-level reasoning, while also providing tools for instructors to monitor student progress.

To support development of this product, several intermediate products are necessary. First, development of QR applications in a variety of science domains needs to be encouraged and supported. Based on these example QR models, exercises and assignments can be developed that capitalise on QR's potential to facilitate causal reasoning by allowing students to interact with the model. Development of lectures that incorporate QR representations of important, domain-specific concepts also needs to be supported. With increasing development of QR models, assignments and exercises, and lectures for a given domain, integration of QR approaches with traditional math-based or conceptual approaches needs to be supported. Such integration will draw on QR's ability to enhance conceptual understanding while also maintaining connections with traditional approaches that are essential for students to understand foundational materials for their domains. Having established a fully integrated QR curriculum for various domains, attention then needs to focus on supporting development of fully implemented, multi-media, interactive models that can take the place of, or at least be integrated with, traditional textbook-based and paper-based learning.

A good example of the need for this type of tool can be seen in ecology. That is, an approach to teaching ecology using QR technology as a means to convey knowledge, including university education, schools, public education, and life long learning. In this respect one important factor will be the provision of a textbook accompanied by an interactive CD-ROM including example models, exercises, assignments, and fully developed ecological lectures. This also requires an organisation and sequencing of the subject matter and underpinning each of the topics with ideas of using QR to clarify concepts. The needs of ecology also drive the next type of tool.

3.2 Advanced QR-based Modelling Environments

Ecologists need means to capture, articulate and represent their knowledge that better fit the idiosyncratic characteristics of ecological knowledge. That is, ecological knowledge is often qualitative, incomplete, fuzzy and uncertain, conceptual, and frequently expressed diagrammatically and verbally. Not being able to sufficiently represent this knowledge in a computer-processable format, preserving its unique characteristics, 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 knowledge.

3.3 Interactive Articulation Devices

A model building environment that allows learners to articulate knowledge (particularly conceptual models) and by doing so, learn about a domain. In order to be effective, such an environment should have the means to criticise the model, help the learner de-bugging the model and effectively organise the model content. In addition such a tool should provide the means to allow diagrammatic sketching of ideas and conceptual knowledge and have this automatically transformed into simulations. Other means that might aid the learner in knowledge articulation will be having resources of previously defined models and model parts.

By year 10, the goal is to develop a model-building framework that facilitates learning by modelling using QR. Learning by modelling using traditional approaches has been shown to be effective for enhancing student understanding of causal relationships and dependencies, but is often hampered by mathematical complexity of knowledge representations, or limited in utility because of static, graphical representations. QR has to capacity to overcome these hurdles, but is currently hampered by limited user-support for model building and convenient technologies for transforming mathematical and graphical / conceptual representations into QR representations.

To overcome these hurdles, some technologies and intermediate products need to be developed. First of all, currently available QR engines need to be enhanced by providing online, query-able help support, with the goal of developing intelligent, context-sensitive help. These technologies would support development of advanced QR-based modelling environments. A foundation of QR is development of appropriate quantity spaces, i.e., identification of relevant landmarks. Technologies need to be developed to extract these landmarks from diagrams and data, with the goal that the process will be semi-automated. A product related to these technologies would be automated sketch-to-model translation tools, where the modeller-student sketches a conceptual model on the computer and the QR modelling environment translates the conceptual diagram into a running simulation model. Technologies related to this product goal include advanced software for model debugging, which would alert the modeller-student to potential logical errors or omissions (e.g., an included component with no connections to other components). The next technological step in model building that needs to be supported is coaching. With coaching, the student will have full interactivity with the modelling environment on the fly, with both the ability to ask questions about what should be done next, and alerted to potential errors during model development (as opposed to running a debugger manually). The next important technology to be developed should be tools to support collaborative model building. Collaborative learning is a proven method to enhance understanding, because of the various viewpoints different students bring to a given exercise. Collaboration can be either simultaneous or sequential, where a modeller-student adapts (re-uses) a previously developed model to a new purpose. In this regard, the modelling coach should provide the important function of explaining how the model works to the new / different user. Dedicated communication tools also need to be developed that allow collaborators to communicate about specific problem areas in an efficient way (e.g., linking a question / answer page to views of model fragments or scenarios, where the authors' attention is immediately directed to the problem area). Such communication tools will also support the important task of model documentation, which will be important to sequential collaborators. In the end, the resulting technologies will feed into an integrated articulation device, where the integration is between the modelling environments and one to several users.

3.4 Autonomous Science-bots

Science-bots are interactive agents that are knowledgeable about a set of topics in science. Each science-bots is specialised in its own area of expertise. They have considerable amounts of domain knowledge and are able to address learners in helping them to acquire knowledge, understanding and awareness. Science-bots recognise and know the informational needs of their learners and users and adjust their communicative interaction so it is appropriate to the specific user. Additionally, they can 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 criticise ideas and thoughts presented to them.

Science-bots can be further specialised in terms of addressing specific user groups such as tourists, decision makers, politicians, and managers. In addition to the above, science-bots will than have capabilities such as generating demonstration examples, ranking solutions, developing argumentations (pros and cons), and performing sensitivity analysis and model critiquing.

3.5 Autonomous Training-bots

Autonomous training-bots are in fact a special class of science-bots. They focus less on knowledge transfer related to institution (universities, schools, etc.) defined learning goals. Instead they operate side-by-side with workers (for instance, in factories or business oriented environments) providing online help and support these workers with performing their tasks.

4 Technology

To achieve the goals and address the vision presented above we need to formalise methods of qualitative knowledge representation. These include development of appropriate qualitative vocabulary and reasoning capabilities for representing complex factors. These include support quantity space (landmarks) generation, multiple timescales, spatial knowledge, model assumptions and dimensions.

In addition it should be pointed out that model building is a difficult task and needs to be supported via help facilities, coaching support, peer collaboration, mentoring and shadowing. To further aid learning and improve process efficiency, an additional goal is to facilitate collaborative model building. That is having modellers learn from re-using and further developing one another’s work. Moreover, the adaptation and re-use of models from within and between domains should be supported.

The starting technological position for the developments explored here is:

- Basic QR engines
- Limited paper-based help
- Basic communication infrastructure (internet)
- State-of-the-Art technology in artificial intelligence and education (AIED)
- Isolated solutions / ideas to integrate qualitative and quantitative simulations

4.1 Online Query-able Help

Online query-able help should support QR-model construction by providing useful information whenever required. Currently, online query-able help is available for products, e.g., text-editors. The underlying concepts should lead to a system that helps the user when developing a QR-model for a specific domain.

4.2 Knowledge Visualisation / Diagrammatic Representation

Understanding model and model construction is a creative process. Currently, logics and to some extent modelling languages, are available for model construction. As a consequence the construction of models and reasoning about the models requires the user of such systems to have a good understanding of the language used. That is in order to prevent that the user from concentrating less on the really important parts of the model and the reasoning process. Therefore, knowledge visualisation and diagrammatic representations of models are required. They not only help to understand models very quickly but also provide means for a natural interaction with the model during the model building process.

4.3 Reasoning with Multiple Timescales / Model Assumptions / Model Dimensions

Currently, modelling is limited to handling single time scales. The use of assumptions describing the decisions that are relevant to the model is at least limited. Moreover, multi-model reasoning, i.e., switching between different levels of abstraction and different views is currently not supported. Therefore, it is a requirement to provide a theoretical basis of modelling with multiple time scales, model assumptions, and the handling of multiple models during reasoning. This holds especially for the educational domain, where almost all models have to consider multiple time scales, assumptions, and different levels of abstraction. For example, when teaching electrical engineering the teacher has to consider different types of models, e.g., dynamic vs. static models, and switch between them whenever appropriated for explaining the underlying processes.

4.4 Context-sensitive Help

Context-sensitive help provides useful knowledge in a particular situation during the QR modelling process. In contrast to online query-able help the presented information depends on the current state and not on the selection of a menu item. Hence, this technology will substantially improve modelling.

4.5 Development of Ontologies / Language Standardisation

A standardised language for describing models in the domain of model-based and qualitative reasoning has been in discussion for the last decades. Some contributions to language standardisations have been published, but so far with limited success. Although, the lack of a standardised language has almost no influence on model-based technology in general, it is a requirement whenever models have to be distributed, communicated, and reused. This is of particular importance for educational software using QR technology.

4.6 Automatic Question, Answer and Explanation Generation

The creation of questions, the proofs of answers, and the generation of informative explanations out of available model, is currently not supported. Almost no research in these areas has been undertaken. The results, for example in explanation generation, are far away from being satisfactory and useful. For a teacher it is very important to ask questions, proof, correct the given answers, and give explanations for a particular domain, e.g., physics. Hence, these tasks are crucial for educational software agents in a particular domain.

4.7 Model Debugging Software

Modelling is a very creative process that is usually incremental. The outcome of a model should cover the important aspects of a system. During this process the model has to be validated. In case of detected differences between the desired model's behaviour and the real outcome of the model, the model has to be improved.

4.8 Integrated QR-Math Simulators

Such simulation technology is able to generate an integrated combination of qualitative and quantitative simulations, providing the advances of each of the technologies as well as being able to automatically transform the representation from one format into the other. Special features of this technology include, qualitative explanation of complex mathematics models, automatic extraction of landmarks from graphs, and support the understanding of complex differential equation systems.

Graphical Roadmap

	Now		2 Years		5 Years		10 Years
Drivers	Decline in science education popularity		Addressing learner information delivery needs		Immersing (motivating) interactive simulations		Open source software availability
	Need to simplify subject matter complexity			Interactive subject matter explanations			Commercial software and education materials
	Limited teaching resources			Support student assessment	Support peer collaboration / learning		
	Project-orientated learning	Modelling as a means to learn	Easy to use modelling environments				Enabling Communities of practices
		Distance-Learning	Support student - teacher interaction		Reduce gap between people with and without access to knowledge		
		Life-long Learning			Disseminating scientific results to the general public		
		Ecological awareness			Educate stakeholders	Eco-friendly tourism	Sustainable development
	On the job training		Easy to develop training systems				

	Now		2 Years		5 Years		10 Years
Products		QR examples	Exercises and assignments	Full QR-based lectures	integrate QR approach with traditional curricula	QR-based curricula for sciences ready for distribution	QR-based curriculum available on CD, textbooks, or other platforms
	Drawing and diagramming tools / Math tools / QR-based modelling prototypes		Advanced QR-based modelling environments		Automated sketch-to-model translation tools		Interactive articulation devices
	QR prototype learning environments / QR science model examples / Traditional information systems / Textbooks		QR knowledge (incl. models) repositories in different domains based on textbooks and other teaching materials		Personified / personalized user interfaces addressing specific domains and user groups		Autonomous science-bots
	Data monitoring devices / math model-based training systems / QR-based training system prototypes / Paper-based user manuals / (Online) help systems			QR embedded simulations based on design and engineering specifications		Authoring environments for creating training software	Autonomous training-bots
							QR-based learning portal

	Now		2 Years		5 Years		10 Years
Technology	Basic QR engines		Reasoning with multiple time scales / model assumptions / model dimensions	Reasoning from diagrams	Semi-automatic landmark recognition	Representation of spatial knowledge	Advanced QR engines
	Limited paper-based help	Online queriable help	Context-sensitive help	Model debugging software	Coaching model building	Supporting collaborative model building and model re-use (incl. dedicated communication tools)	Intelligent QR model-building support
	Basic communication infrastructure (internet)		Development of ontologies / language standardization		Dedicated infrastructure for sharing and re-using models and model parts		
	State-of-the-art technology in artificial intelligence and education (AIED)	Knowledge visualization / diagrammatic representation	Automatic question, answer, and explanation generation		Learner modelling	Automatic curriculum planning and subject matter sequencing	
	Isolated solutions / ideas to integrate qualitative and quantitative simulations			Qualitative contextualization of math models and simulations	Qualitative explanation of complex math models	Model transformation technology	Integrated QR-Math simulators
			Scenarios / assignments	Ranking / sensitivity analysis / impact assessment	Model critiquing / constructing argumentation		

5 References

Bessa Machado, V. and Bredeweg, B. Investigating the Model Building Process with HOMER, pp1-14 in proceedings Qualitative Reasoning for Intelligent Tutoring Systems Workshop at ITS2002, 2002.

Biswas, G. Schwartz, D. Bransford J. Technology Support for Complex Problem Solving: From SAD Environments to AI. Chapter in Forbus, K. and Feltovich, P. (Eds.) (2001) *Smart Machines in Education: The coming revolution in educational technology*. AAAI Press.

J.S. Brown, R. Burton, J. de Kleer, Pedagogical, natural language, and knowledge engineering techniques in SOPHIE I, II, and III, in: D. Sleeman, J.S. Brown (Eds.), Intelligent Tutoring Systems, Academic Press, New York, 1982.

Forbus, K.D., Whalley, P., Everett, J., Ureel, L., Brokowski, M., Baher, J. and Kuehne, S. (1999) CyclePad: An articulate virtual laboratory for engineering thermodynamics. *Artificial Intelligence*. 114, 297-347.

Salles, P.S.B.A, Pain, H. & Muetzelfeldt, R.I. Qualitative Ecological Models for Tutoring Systems: a Comparative Study. In P. Brna, A. Paiva and J. Self (eds). *Proceedings of EuroAIED95*, Fundacao Calouste Gulbenkian, Lisbon, pages 226 - 232.

6 Document History

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