Vision for the Future of Education Systems based on Qualitative Reasoning

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Abstract

This paper presents the roadmap that was developed by the MONET task-group on Education and Training MONET is a European Network of Excellence on Model-based Systems and Qualitative Reasoning (monet.aber.ac.uk). The roadmap envisions the future of education systems based on Qualitative Reasoning.

1 Introduction

Tutoring and training was one of the earliest application areas using Qualitative Reasoning (QR), e.g. [7, 11, 13]. At present, there are several types of QR 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, such as teaching thermodynamics [9], teachable agents [2], cognitive support tools [12], and workbenches for developing conceptual knowledge [3, 1, 10, 4]. For surveys of qualitative reasoning and education see [8, 6, 5].

QR technology is of great importance for developing, strengthening and further improving education and training on topics dealing with systems and their behaviours. QR technology 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, 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 a result, the full potential of qualitative models as a key component of tutoring systems and interactive learning environments is still to be realised.

In this document we present a Roadmap that envisions a future for educational software based on QR technology over the next 10 years and beyond. The document is divided into four sections. The section on *drivers* discusses the needs from the field: what is currently needed and how will that change in the near and far future. The section on *products* shows how we can address those needs by developing tools, software and other dedicated products. The section on *technology* discusses the technological improvements and breakthroughs that need to be realised in order to construct those products. Finally, the section on *resources* briefly illustrates how the necessary work may be accomplished by defining projects and related efforts to tackle the technological requirements.

2 Drivers

There are people who have an interest in learning for their own benefit, albeit for different reasons such as citizens, stakeholders, and decision makers. Each of these groups have learning needs, which we consider 'drivers' because they *drive* the development of new products and thechnologies. Some of these needs apply particularly to students in educational institutions. There are also employees and trainees in industry who require knowledge in order to develop in their career or to accomplish their job-related tasks. This section describes these drivers.

2.1 Decline in Science Teaching

There is a *need for improving science education in schools* (and universities) and a *need to handle subject matter complexity*. In fact, it seems that in formal educational settings there is a decline in the popularity of science education, as less people are choosing an education in science. Another problem is that the number of women in science curricula is low. There is also the argument of 'perceived' complexity: science material is perceived to be more complex than it actually is because of methods used to teach it actually get in the way of learning. A further complicating issue is the *limited teaching resources and materials and inadequate assessment techniques* that are currently available to most institutions.

QR technology can be used as an aid to supplement both the teacher and resource shortage. Increasing the usage of the interactive nature of models and simulations makes science education more interesting and easier to understand for those involved. However, there is also a *lack of awareness of QR technology* and its potential among the developers of educational materials, educators, politicians, and commercial enterprises that hinders the take-up, use and further development of this technology.

2.2 Learning by Model-building

There is a movement to teach students using *project-oriented learning*, which fosters collaboration, hands-on experience and a self-organising approach to learning. Educators want students to actually 'process' the subject matter, instead of just 'storing and reproducing'. Using QR and *modelling as a means to learn* 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. With modelling, all the information is present but 'hidden' in a conceptual structure. 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. Hence, *easy to use modelling environments* are needed that allow a wide variety of learners to articulate and develop their *conceptual* understanding of scientific phenomena and system behaviour.

2.3 Interactive Subject-Matter Explanation

In an educational setting there is a need for interactive simulations that explain scientific insights, hence the need for *interactive subject matter explanations*. The idea here is that these are more specific and focus on key scientific aspects whose explanation is captured or enabled by the simulation. As examples think of explaining friction, heat-exchange, the subtle distinction between the notion of 'heat' and 'temperature', predator-prey behaviour, and so forth. 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. Ultimately, there is a need for *QR based education software and teaching materials*.

2.4 Immersive Software

The potential for 'learning through play' has been well developed for the education of the young, but it has applications for adult education as well. Motivating a learner will increase their willingness, and subsequently their ability, to learn. Consequently, there is need for *immersive (motivating) interactive simulations*. Collaborating with peers may be a way of getting learners immersed. Taking a game-oriented approach is another. 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.

2.5 Collaborative Learning

Many educational researchers have discussed the need and benefit of a collaborative approach to learning in regular educational settings, hence the need to *support peer collaboration and learning*. There is also a need to easily manage and organise the teaching materials between students and teachers as well as the communication about those materials between the participants, hence *supporting student-teacher interaction*. In order to make that happen, infrastructure needs to be established that supports a collaborative approach to learning. From a model-building perspective this implies means to easily share, evaluate, and re-use models created by peers. Particularly needed is the ability to tailor currently existing digital workspaces for education to more easily support version management of models (such as competing models, alternative models, refinements, etc.). Another aspect concerns the ability to comment on models, both for learners and teachers, in order to explain, criticise and otherwise verbally detail issues relevant to models and model parts.

2.6 Assessment

Collaborative and distance learning have the goal of increasing learning opportunities, but teacher resources remain critically limited. There is a need for other means to *support student assessment* and *learning progress*. Next to individual assessment, teachers need means to assess how students differ and how groups behave. Models can aid in this process. Assessment methods need to be able to take the quality and appropriateness of models created by students into account. Additionally the same approach can also be used to *support self-assessment*. Learners can have their knowledge tested by the system both in a formal set of tests or interactively as they work through the model. Also, the simulation results produced by a model are themselves a means of evaluating its correctness, which is particularly important when that model was actually created by the learner.

2.7 Science Education in the Community

Humans continuously explore and further advance their understanding of the physical world and make increasingly more complex devices to assist them in their daily life, work environments, and leisure time. There is a need to design teaching methodologies that support humans in coping with this complexity, hence the *need for science education in the community*. This means that models should be provided that may have a high degree of complex scientific 'knowledge', but the user should be able to interact with a simple front end that supplies them the information (or answers) that they want, and most likely without going into complex scientific considerations that they may not understand, or may not even want to understand.

An important feature of such facilities should be that it allows the user to not only understand, but also provide the ability for the users to build up an argument (to defend and explain their understanding and standpoint). Also, citizens, stakeholders, and decision makers typically develop an interest in scientific problems because of matters they are confronted with in their everyday life. Often they are a group who is affected, or who wants to enforce some approach for the future. Therefore, the idea of project-oriented learning can be refined here into *problem-oriented learning*.

Life-long learning gives the opportunity for people to continue their study long after they pass the 'usual' educational age. Tourists may use *distance learning* through a wireless-PDA to inform them of the area of jungle around them and in doing so further their *life-long* interest in plants.

In time we anticipate that the necessity for science education in the communities will proceed along with the following emerging needs that need to be addressed. First, before information can be delivered to a community it is important to *analyse the information delivery needs* of the target audience. Means are needed to actually do such assessments. Note that, because these assessments have to happen repeatedly, they are a kind of continuous process, addressing new and different communities, as well as changing communities, as time passes. Second, when information needs can be identified, this provides the gateway for *disseminating scientific results to the general public*. This issue is a little deeper than the act of simply sending out the original scientific information to the public at large. The information will need to be presented in the manner that it is most acceptable to and absorbable by the group for which it is intended. This will lead to the same information being packaged differently; potentially this could be different for every user group for which it is intended. Third, the discussion so far assumes that the audience is able to access the information being disseminated, regardless of the form and specific content. However, this is not always true. Communities exist that have no access to proper information channels. Hence, there is a need to *reduce the gap between people with and without access to knowledge*. Fourth, rather than simply receiving and understanding information, as is suggested above, the next requirement is that the user takes that information and uses it as a basis to formulate an opinion, decision, or solution to a problem. Thus, there is a need to *support decision-making and argument building*.

2.8 Availability of Resources

Use of QR technology for distance learning requires access points where students can access models, possibly made by experts, educators, and peers. Hence the need for *making information resources available in order to address user needs*. The idea is that before, during, and after the learning process there are resources that you can go to in order to investigate the areas in which you are interested. Whether someone is merely curious about a particular plant or animal, or if the person wants to embark on learning another discipline, the information should be available. At present we have the World Wide Web that simply lists information. This will change into information delivery systems focused at particular groups. This development will continue all the way to intelligent tutoring systems that can talk to you in order to assess both what information you want and how you would best absorb this information.

When communities have developed solutions to problems and built arguments explaining and possibly defending that solution, it is only logical to store those and make them available to others who face similar or related problems. After all, a great deal of effort may have gone into their development and it seems a waste if that knowledge (and time) were not to be made available for re-use. Consequently there is a need to *save, store, and facilitate re-use of QR solutions to problems*. This resource must be more than a simple on-line information storage system. It must be a repository for models and model parts that have been used in the past to aid in understanding of previously modelled issues. Maybe it should also be a place for storing partially modelled issues.

2.9 On-the-Job Training

The increasing complexity in job- or task-specific skills is creating a need for employees to update their skills, hence *on-the-job training*. Providing this skills training in the workplace is efficient use of resources and employee time. Many tasks, such as diagnosis or interpretation of data, rely on an understanding of the underlying system, and training systems based on QR technology can provide the depth of training detail that is required for such tasks and can deliver it remotely via the World Wide Web.

2.10 Communities of Practice

Communities of practices 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 practices may exist or come into being in many diverse areas, including schools, universities, industry, managers and other stakeholders such as tourism and ecology workers. To realise communities of practice the necessary infrastructure needs to be created to support collaborative distance learning (and working) in terms of model sharing and tools to communicate and discuss model content and features (see also driver 2.5).

3 Products

Current QR products that are used in educational settings are mostly prototypes. If we distinguish between *tutoring* and *training*, tutoring has *tools* for learners to articulate knowledge and *models* for learners to interact with, which can be regarded as prototype *learning environments*. On the training side a whole range of simulation-based systems have been developed and studied over the last two decades.

3.1 Towards QR-based Curricula and Teaching Materials

By the end of the 10-year period covered by this Roadmap, our goal is to develop curricula and related teaching materials that are integrally based on QR technology 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, collaborative-learning, and high-level reasoning, while also providing tools for instructors to monitor student progress.

To support the development of such products, several intermediate products are necessary. First, development of *QR models 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. Alongside increasing development of QR models, assignments, exercises, and lectures for a given domain, QR and traditional (e.g., math-based) approaches need to be integrated. 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 (related to driver 2.1). Having established a fully integrated *QR curriculum* for various domains, attention then needs to focus on supporting development of fully implemented interactive models that can take the place of, or at least be integrated with, traditional textbook-based and paper-based learning. An interesting track to pursue is *edutainment* and *immersive simulations* as a means to increase motivation and interest on behalf of the students for certain topics (see driver 2.4). Ultimately, a *QR-based learning-portal* should emerge which can be used for teaching and training for a variety of domains and levels of education.

3.2 Tutoring using QR-based Tools and Models

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 that are frequently expressed verbally and diagrammatically. QR technology can provide computer-based facilities to represent and reason with this kind of conceptual knowledge.

An *Interactive Articulation Device* is a model-building environment that allows learners to articulate knowledge (conceptual models) and by doing so learn about a domain. 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, 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, but is currently hampered by limited user-support for model-building and convenient technologies for transforming mathematical, graphical and conceptual representations into QR representations. Tools should provide the means to allow *diagrammatic sketching* of ideas and conceptual knowledge and have this automatically transformed into simulations. In order to be effective, such an environment should have the means to *critique* the model, help the learner with *debugging* the model and effectively *organise* the model content. The following products are viewed as intermediate steps.

Most QR software is currently difficult to use, because it requires advanced programming skills to build models. Therefore, model construction tools are needed that allow learners and teachers to articulate their conceptual understanding in a diagrammatic way, just as if they were drawing on a piece of paper or a blackboard. The next goal would be to augment them with support. Particularly, on-line help and the means to automatically critique and debug the models must be created. Also, the means are required to help users organise and structure their models and the model-building process. It is then expected that these advanced modelling environments will become more flexible and allow multiple representations to be easily transformed into each other. This is the idea of *automated sketch-to-model translation* tools, the ultimate goal of which would be the ability to literally draw (sketch) instead of selecting things from a predefined list. This would make a considerable impact on the next generation of model-building products. Another area in which progress is needed is collaborative learning and the construction of knowledge. Infrastructure and model cut-and-paste facilities are needed to share, review and re-use models and model parts, among participants (see drivers 2.5 and 2.9). Note that this indirectly also stresses the need for advanced model organising and assessment tools. When each of these products has become well established, they can be integrated in interactive articulation devices that provide easy-to-use means for knowledge capture and support users in the model construction as well as in collaborating with other model builders.

The concept of *autonomous science-bots* further advances the idea of individualised support, by the building of resources of previously defined models and model parts, and coaching (also addressing drivers 2.7 and 2.8). *Science-bots* are interactive agents that are knowledgeable about a set of topics in science. Each science-bot is specialised in its own area of expertise. They have considerable amounts of domain knowledge and are able to assist learners by helping them to acquire, understand, and become aware of knowledge. 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 may 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 science-bots will have capabilities such as *generating demonstration examples*, *ranking solutions*, *developing argumentations* (pros and cons) and performing *sensitivity analysis* and *model critiquing*.

To arrive at science-bots, two intermediate products need to be developed. The first one is concerned with capturing considerable amounts of domain knowledge, based on textbooks and other teaching materials. Second, a set of personified and personalised user interfaces must be established in order to address the needs of specific users and domains. Personification refers to the use of avatars and related interface objects that help users in feeling that they interact with caring agents. This is important for increasing the motivation of users. Personalisation refers to the science-bots having knowledge of the user's current knowledge-state and being able to adapt and optimize the interaction from the learner's point of view.

Autonomous training-bots are a special class of science-bots. They focus less on knowledge transfer related to goals defined by educational institutions (universities, schools, etc.). Instead they operate side-by-side with workers (for instance, in factories or business-oriented environments), providing online help and support for these workers to perform their tasks. An intermediate class of products are *QR-embedded simulations* based on design and engineering specifications. Numerical simulations, although precise, typically lack the vocabulary for a software coach to properly explain simulation results. By embedding such simulations in a QR vocabulary, the automatic generating of explanations becomes possible. Once these products are in place, the next step is to aid the construction of such embedded simulations, by developing authoring tools that help designers in building them.

4. Technology

This section discusses the technological advances that need to be realised in order for the products to be developed and based on that, drivers addressed.

4.1 QR Engines

To arrive at *advanced QR engines* that are able to deliver the reasoning power required for addressing the user needs that we outline above, a range of significant breakthroughs and improvements are essential. Currently a small set of *prototype basic QR engines* is available. The first thing to work on is to improve those engines, possibly by effective re-implementation of them, to arrive at a set of *operational basic QR engines* that can be used for multiple domains. An important aspect of that effort should be to guarantee that the reasoning capability is in good shape (in line with current, established ideas of how that reasoning should be done), with as few software bugs as possible. This should then be augmented with a proper *Graphical User Interface* (GUI) so that users can use the software easily and no programming expertise is required. The process should then move on to enhance the reasoning capabilities, particularly addressing issues such as *reasoning with multiple time scales, model assumptions, and model dimensions*. Although some initial research has been carried out to address these issues, a coherent view has not yet been established and no QR engines are currently available that facilitate easy incorporation of these aspects.

To further enhance the interaction with users, the next challenge is to use *reasoning from diagrams*. This concerns mainly the input for a QR engine (e.g. sketching a scenario or a set of model fragments). The user should be given easy-to-use diagrammatic facilities to flexibly draw a 'concept map' from which the QR engine can infer the knowledge involved. An important aspect to be solved here is a formal account of the diagrammatic language and the underlying ontology. Such a formal account will be the basis for the QR engine to parse diagrams and simple drawings automatically (see also section 4.4).

Finally, there is the issue of *semi-automatic landmark recognition* and *representation of spatial knowledge*. Developing a set of landmarks for quantities in a particular domain is a non-trivial problem. Smart support on establishing landmarks and deciding on quantity spaces is therefore required. A rather advanced version of this would be to have technology that, by monitoring quantitative data in some domain would be able to (semi-) automatically infer the relevant landmarks. Another aspect concerns the representation of spatial knowledge and the integration of that with more traditional QR approaches (e.g., state transitions). Current reasoning capabilities essentially assume a fixed structure. More advanced reasoning becomes possible when QR engines would also be able to reason about the structural constellation and how that might change.

4.2 Help on Using QR Engines

There is a need to provide *intelligent QR model-building support* that goes well beyond *the limited paper-based help* that is currently available. To arrive at this goal, a series of intermediate technological improvements needs to be realised. First, *electronic queriable help* should support QR model construction by providing useful information whenever required. Second, *context-sensitive help* provides useful knowledge that has been tuned to a particular situation. In contrast to online queriable help, the information presented depends on the current state of the model or the simulation situation a user is in and goes beyond the selection of predefined menu items. Hence, this technology provides a substantial improvement in supporting modelling and the use of QR engines.

Modelling is a very creative process, however, it is usually incremental. During this process the model has to be evaluated. In case of differences between the desired model's behaviour and the real outcome of the model, the model has to be improved. Hence the need for *model debugging software* that alerts the modeller to potential logical errors or omissions (e.g. an included component with no connections to other components). In addition, there is a requirement for *advanced model navigation and management software*, as well as for actually *coaching model-building*. With coaching, the user 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 being alerted to potential errors during model development (as opposed to running a debugger manually). Finally, when infrastructure has been developed to support collaborative working and learning (see below) and models can be shared, there will be a need to provide help on that, hence, *supporting collaborative model-building and model re-use*.

4.3 Collaborative Model-Building and Model Sharing

Collaborative learning is a valuable 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 adapts (re-uses) a previously developed model for a new purpose. To arrive at a *dedicated infrastructure for sharing and re-using models and model parts* (including dedicated communication tools), a number of earlier breakthroughs are required. One concerns the development of ontologies and language standardisation. Standardised languages for describing models using QR technology have been discussed and 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 re-used. This is of particular importance for educational software using QR technology. It is expected that establishing a *network of experts* will aid the progress towards standardisation. This goal also requires *dedicated tools for communication* 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.

4.4 Teaching with Models

Autonomous science-bots do not necessarily have to be knowledgeable about everything within a certain domain in order to be effective. They would already be very useful if they were able to communicate with a learner everything important to a certain model or a set of interrelated models. In fact, this is the approach we adopt here and which we consider achievable from a scientific research point of view within a reasonable timescale. This hypothesis is based upon current *state-of-the-art technology in Artificial Intelligence and Education (AIED).*

Interface technology must be developed that allows users to interact with QR-based products using *knowledge visualization* and *diagrammatic representation*. This means not only delivering the help required to understand models more quickly but also providing channels for a natural interaction with the model during the model-building process. Special attention should be given to *automatic diagrammatic reasoning*. Among others, the engine should be able to automatically draw diagrams that show the information inferred by the engine (see also section 4.1).

The next set of technological improvements concerns *automatic question, answer and explanation generation*. Particularly, automated question generation (and the accompanying automated answer generation) has been given little attention by the AIED research community. Of course, such means are of prime importance for communicative interactions in general, not only when a learning experience is based on QR technology. Teachers typically ask questions, evaluate the given answer and provide corrections and explanations when needed by the learners. The interaction can become even more advanced when answers are not only evaluated in terms of correct and incorrect, but when the software also tries to establish an explanation of why the learner gives an incorrect answer, i.e., performs *diagnosis and assessment of learner errors*. When such a diagnosis can be set up, the feedback can be made even more focused towards the specific needs of the learner. More advanced is the issue of *learner modelling*: the goal of establishing a model of the learner's knowledge state over a period of time and not just following an answer to one question. What are the typical problems that this person has with the subject matter? What motivates him or her most? Maybe even memory specific features could be included. Over time, the science-bot starts revisiting and re-introducing some of the earlier material because it knows that by now the learner may have forgotten this information. Finally, there is a need to develop technology to do automatic curriculum planning and subject-matter sequencing. This will give the science-bots the ability to select, organise and sequence the subject matter in a manner that best fits the present educational situation.

4.5 Integrating QR and Mathematics

Qualitative models are essential for communicative interactions. Without the vocabulary and reasoning capabilities that these models deliver, a computer-based learning environment will not be able to effectively automate the interaction with learners. On the other hand, numerical simulations and other traditional approaches from mathematics are valuable for calculating precise results when enough resources are available. Ultimately, technology should be established that facilitates 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. To arrive at such fully *integrated QR-Math simulators* the following intermediate technological advances are envisioned. The first step is to encapsulate quantitative solutions in a qualitative vocabulary: *qualitative contextualization of mathematical models and simulations.* These embedded models can then be used to automatically *generate qualitative explanations of complex mathematical models*. Next, technology should be developed to easily switch between qualitative and quantitative models and simulations of a phenomena or system behaviour, hence *model transformation technology*. Special features of this technology include automatic extraction of landmarks (see also section 4.1).

4.6 Model Evaluation and Assessment

When models and their simulation results become an important resource for education and training, and communicative interactions in general, then there will be the need for the means to automatically assess the quality of models. Benchmarking using standard *scenarios and assignments* should be possible. More advanced technology is needed for *ranking, sensitivity analysis, and impact assessment* with respect to models and their results. Still more advanced, are the means for *model critiquing* and means for *constructing argumentation* in favour of (or against) a particular model. Providing automated solutions to model evaluation and assessment is a serious challenge, because it is quite possibly one of the least developed areas of research within the QR community.

5. Resources

Determining the resources needed to implement the vision outlined in this Roadmap is a difficult task. Our suggestions in this section should be seen as a very rough estimate. But as any estimate is better than none, we have made an attempt. Let us assume that most of the technological solutions that need to be establish take the work of an average PhD project, say four years. In addition, some issues such as *reasoning from diagrams* and *model transformation technology* are rather complex. Let us assume that topics such as these require four projects each. In total there are 26 technological 'clusters' to be solved (see section 4). If we assume that 2/3 of these are of average complexity and 1/3 are difficult, we get 17+9*4=53 projects. Each project takes four years, resulting in an effort of 53*4=212 person-years for research (equal to 2544 person-months).

Developing products takes effort from companies and commercial enterprises. The technological solutions need to be integrated and transformed (from research prototypes into products for end-users). Let us assume we need four persons working for one year for each product. There are 16 product 'clusters', resulting in an effort of 64 person-years (equal to 768 person-months).

In total, to realise the ideas presented in this Roadmap we need to invest an effort of 276 person-years, equal to 3312 person-months. Over a period of 10 years this could be realised by a group of 28 people. This is not a very large effort when compared to the significantly larger amount of resources that companies such as Microsoft spent on developing their Office package or their Windows operating system.

6. Conclusion

This document presents a Roadmap that envisions how QR technology can be used to advance automated tutoring systems and interactive learning environments. Based on needs—referred to as drivers—products have been defined and the required technological developments have been described. Although current research on the use of QR technology for educational purposes is promising, a significant amount of additional effort is required to address the drivers and actually have products that end-users can effectively use for their own benefit. Clearly, the Roadmap shows that such investments are essential and worthwhile for people to actually profit from the potential that modern QR technology has to offer.

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