Application Oriented Qualitative Reasoning

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Introduction

Work in Qualitative Reasoning (QR) has made many technical advances and current techniques are now adequate for some real world problems. As a result, it is time to think about further applications of QR. In order to do so, it is helpful to have a summary of what has been done to date. This helps to provide a picture of in which application areas the techniques have been applied, and who is working in each area. In this paper, we provide a summary of application oriented work using qualitative reasoning. Because of the large number of projects summarised, there is only a short description of each project.

The first part of this paper comments on the important mathematical aspects related to qualitative algebras and qualitative calculus and provides a brief overview of the most common representation formalisms and reasoning algorithms used so far, with the related references. It is not the purpose of this paper to provide a detailled technical survey. This section aims at helping the non experienced reader to relate the described project to the type of technique been used. It is also not the purpose of this paper to comment on the range of techniques in use. It is acknowledge that in some places the text is in the form of short comments rather than flowing sentences. It is after all, not yet a formal paper.

What is application oriented work? For the purposes of this summary, this is reports of work in progress or completed where the examples given are more than toy or generic examples. For example, when an approach to qualitative simulation is illustrated by an example of the control of a greenhouse heating system. This definition includes many projects that are not real applications, or that will go beyond the laboratory work of a research group. They do serve to illustrate the potential application areas of QR and how the techniques apply to typical industrial problems.

At this time, there are very few real industrial QR systems, or systems that are designed for day to use. This reflects the state of the applications of QR. It is hoped that a similar summary in a few years will paint a very different picture. Although many application oriented examples are given in this paper, very few are being developed with the intention of making a usable application. Many are used as realistic vehicles for research only.

Note that some of the work by major researchers in the fields of qualitative reasoning and model based diagnosis is not included in this summary. This is because it is a summary of the application oriented examples, rather than the technical approaches.

The second part of this paper is organised by broad categories of application domains. Within each domain, a summary of projects or ongoing work is given, with an indication of the techniques being used and the current status of the project. In general this information was taken from published technical papers, so in many cases some of the interesting information is not given.

I. Some representation formalisms and algorithms used in QR

This paper presents some of the important mathematical aspects related to qualitative algebras and qualitative calculus and provides a brief overview of the most common representation formalisms and reasoning algorithms used in Qualitative Reasoning [83].

I.1. Qualitative Algebras and qualitative calculus

It is common in QR to assume that physical variables are continuously differentiable functions of time and to discretize their value range into a number of finite qualitative values, generally ordered, which is called the *quantity space* of the variable. As it is often refered to $\Re$ as the value range of physical variables, the quantity space is generally a partition of the real line in which a qualitative value coresponds to a subset of $\Re$ *(for instance, see Fig. 2)*. The idea of qualitative algebras is to be able to perform the same algebraic manipulations, like sum and product, as in $\Re$ by using a qualitative calculus consistent with the real counterpart.

Qualitative Algebras can be ranged in a continuum going from the poorest informative partition (sign algebra) to the more informative one (interval algebra which allows representing even real numbers).

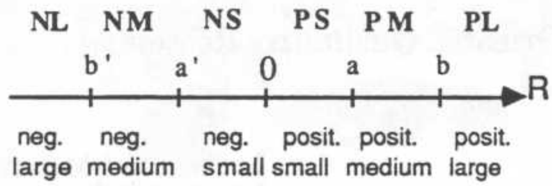

Fig. 2- A special partition of the real line

The most important concept of *qualitative equality* is generally understood as *"possibility of being equal"*. In other words, two qualitative values are qualitatively equal if the subsets of reals that they represent have non empty intersection. An axiomatic of the qualitative equality was provided in [81]. A major difficulty in qualitative calculus lies in that *qualitative equality is not transitive*.

<u>Sign Algebra</u>
This algebra is based on the roughest partition of the real line : negative numbers, positive numbers and zero. The set of symbols is then $S=\{+,-,0,?\}$ where *?* stands for undetermined sign. *?* is necessary to obtain closeness of sum and product operators. Operators are defined in a trivial way, e.g. $+\oplus+ = +$, $+\oplus- = ?$, ...

Although the sign partition roughness certainly induces some limitations, it also offers several significant advantages in terms of interesting mathematical properties :

(1) qualitative equality is transitive if the middle element is different from *?*,
(2) sum and product are associative.

This makes qualitative calculus rather feasible [76]. In particular, a qualitative resolution rule has been proved [80]. Sign algebra is one of the most often used tools in Qualitative Reasoning.

<u>Order of Magnitude Qualitative Algebras</u>
The main limitation of sign algebra lies in that sign knowledge by itself often leads to undeterminations, e.g. $+\oplus- = ?$. More sophisticated structures based on finer real line partitions have then been studied to capture orders of magnitude [81]. These algebras include quantitative information in the *numerical boundaries* which specify a partition of $\Re$. Calculus then requires explicit reference to real numbers.

This causes the fundamental difference relative to sign algebra since a given set of symbols corresponds here to an infinity of partitions of $\Re$ (related to the choice of numerical boundaries, *a, b, a', b'* for the *Fig.2* example). Consequently, symbolic tables for $\oplus$ et $\otimes$ which preserve consistency with real numbers are not unique. However their number is not infinite as the boundary space can be partitioned into equivalence classes, each one corresponding to a different symbolic table. This kind of study has been developed for the partition given in *Fig.2* [64], where the boundary space is the connex domain of $\Re^4$ given by $D=\{(a,b,a',b')\in \Re^4,\ b'<a'<0<a<b\}$. For $\oplus$, it has been shown that *201* tables are possible in the general case. However the *201* tables come down to *2* qualitatively different (i.e. there exists at least a pair of values for which the results are not qualitatively equal in the tables) ones only. In the most commonly used symmetrical case $(a'=-a,\ b'=-b)$ there are *3* possible tables only, which come down also to *2* qualitatively different tables as well. Robustness and precision of these tables have been studied.

These mathematical structures do not have the same interesting properties as sign algebra so that qualitative calculus is more difficult [57]. Besides non transitivity of $\approx$, two other significant problems are encountered : *lack of associativity* of operators $\oplus$ and $\otimes$ and *lack of distributivity*. In other words the same arithmetic expression yields different results depending on processing sequence. It is reassuring that the results are always qualitatively equal, but this means that "minimality" of the solution is not guaranteed. In a simulation framework, this is one of the causes of spurious behaviors. In this case however, spurious behaviors are a subset of those which would be generated with sign algebra. Particular partitions can be proposed to overcome some of these problems [82]. On the other hand, preliminary discussions on the advantages and disadvantages of fuzzy partitions can be found in [27].

I.2. Some examples of QR approaches

<u>The Confluences Approach</u>
Confluences are multivariable linear equations whose parameters take qualitative values. The term *"confluence"* was introduced by *de Kleer and Brown* [24].

In their approach, a system is described by three types of elements : materials, components and conduits. The components act upon materials and the conduits transport materials from one components to another. A component is described by a set of variables, a set of confluences and a set of connections. Then the model of the global system is obtained by assembling the different components.

In their approach, the value range of variables is discretised in three values *{+,0,-}*. Confluences express the constraints linking *variations* of significant variables in the neighbourhood of an equilibrium point. They may be derived by differentiating physical equations at equilibrium for instance. A system may have several modes, each one described by a set of confluences.

De Kleer and Brown approach provides an envisionment. Roughly, and without considering several modes, the first step consists in solving the confluences in the sign algebra. The solutions represent the admissible states of the system are then chronologically ordered in a mythical time axis by using heuristics derived from the properties of continuously differentiable functions like the intermediate value and the mean value theorems. Envisionment takes the form of a diagram in which possible system behaviors appear as sequences of states which the system may go through.

Solving confluences in the sign algebra has been extensively investigated, see in particular [80]. Solving confluences by means of order of magnitude algebras has also been studied [57, 81].

The Relative Order of Magnitude Approach

This approach allows qualitative comparison of entities without refering to any absolute scale. Unlike information provided by qualitative algebras, the information for a given variable is always expressed relative to other considered variables.

The originator of these models is the formal system *FOG* presented in [67]. *FOG* is based on three operators expressing the relations *"negligible in relation to"*, *"close to"*, *"has the same sign and order of magnitude as"*. *FOG* includes one axiom and *30* inference rules which allow propagating initial knowledge.

Operators are used to express relationships between variables, thus providing a static model of the system at some operating point.

Other formalisms, derived from *FOG*, were later proposed to provide solutions to some unsolved problems [20, 27, 53]. In particular, major issues were to make the system accept purely numerical values, and to provide satisfactory answer to the problem of non real transitivity of operators.

The Qualitative Differential Equations (QDE) Approach

This approach was proposed by Kuipers [45] and implemented in the system QSIM. A system is described by three types of elements : varaibles, constraints and operating regions. Operating regions define the different modes of the system. The constraints specify the relations between variables within a given operating region. Basically, the relations between variables are expressed by using the following operators [45] :

- Derivation *DERIV(x,y)* for $y=dx/dt$,
- Sum *ADD(x,y,z)* for $z=x+y$,
- Product *MULT(x,y,z)* for $z=x.y$,
- Increasing or decreasing monotonicity *M+(x,y)*, *M-(x,y)* for $y=f(x)$ where f is an increasingly or decreasingly monotonic function.

The model is therefore given by a *Qualitative Differential Equation* which contains several constraints. Constraints are not solved but are rather used as filters which discard non consistent qualitative states. Filtering is performed in the sign algebra.

QSIM simulation algorithm starts from an admissible initial state, the algorithm finds all possible successor states by using a table of autorized transitions. This table relies on the properties of continuously differentiable functions (notice overlapping with De Kleer & Brown' approach). The second step uses the *QDE* model to filter out states which are inconsistent with some constraint in the *QDE*. Because of inaccuracy inherent in the model, there are generally several admissible successor states. Hence simulation provides a tree whose branches represent possible behaviors in terms of sequences of states. Numerous improvements have been added to the algorithm initial version [31].

The Qualitative Transfer Functions (or Propagation Functions) Approach

As opposed to the three approaches presented above, which do not presume causality, this approach is causal in the sense that the system model is supported by an oriented graph in which the nodes represent the variables of the system and the edges materialise the influences from one variable to another. This formalism is inspired from Automatic Control Theory in which transfer functions are used to relate linear systems output variable to input variable changes. To a temporal function as input, they associate another temporal function as output [4, 16, 48].

In a similar way, *Qualitative transfer functions (QTF)* define a behavioral constraint between input and output variables and capture the type of constraint as well as experimental data like qualitative value of gain, delay, settling time, ... Time is discretized in episodes so that the output temporal function shape is defined a-priori by a piecewise linear function . The a-priori shape of the function is an approximation of well-known responses of numerical transfer functions to classical inputs (steps and ramps).

As the output provided by a *QTF* is a linear piecewise function, it is therefore suitable as input of another *QTF*, which allows propagation of a temporal function through a cascade or a network of *QTFs*. This propagation procedure is at the basis of the simulation algorithm [47].

Propagation functions (PF) introduced by Vescovi [87, 88] also define a behavioral constraint between system input and output variables. However, only steps are considered. *PFs* express the response to step inputs. Input signals (ramp, exponential,...) are approximated by a sum of step signals (called *"perturbations"*) whose magnitude is significant to process experts. Besides, *PFs* are defined as *fuzzy-valued* continuous functions.

The Constrained Influences Approach

This approach proposed by Bousson and Travé-Massuyès [9, 10] is based on a combined use of causality and deep knowledge in terms of mathematical equations. This two levels formalism has been devised so as to overcome the limitation of causal approaches which are not able to capture global constraints, such as balance equations. It has been implemented in the system CA-EN.

Time is represented explicitely as a discrete set of linearly ordered time points, whose resolution is sufficient for the dynamics of the system. The causal model of a process is represented as both a causal network of interacting elementary dynamic systemps, called qualitative automata, influencing one another, and a set of qualitative constraints linking possibly several of such automata.

At the first level, influences include the representation of activation caonditions, time delay and response time. The higher level is composed by functional constraints relating several automata taking the form of mathematical equations whose parameters take numeric interval values.

A cycle of the simulation algorithm includes three steps, run at every clock tick : (1) perturbation propagation in the causal graph using an influence combination procedure [11], (2) variable state updating, (3) states filtering on the high level global constraints.

II. Application oriented work

II. 1. Continuous Processes

Monitoring and Diagnosis

ARTIST: Chemical plant and electricity network
The Artist ESPRIT project (Leitch et al. [50]) is concerned with process monitoring and diagnosis. The main focus is a generic model based diagnosis tool. There are two applications. One is an electricity distribution network and the other is a chemical plant distillation column. It is expected that the final prototype will implement a static qualitative model based approach only. However, the project includes some research on how to perform a diagnosis based on dynamic models (using qualitative simulation). This research is being conducted by Leitch et al. [74, 75] at Heriot-Watt University in Scotland. They are using their own qualitative simulator FuSim which implements a QDE-based approach with fuzzy quantity spaces associated to variables. This is one of the largest model based diagnosis projects in Europe. Partners include Heriot-Watt University in Scotland, Siemans in Germany and CISE in Italy. The project is still under way in 1993.

Bertin, et al [7] describes work at CISE on monitoring and diagnosis of process control systems. The work in this paper was part of Esprit project 820, a pre-cursor to Artist. The authors are now part of the Artist project.

DIAPASON: Illustrated with a pulsed column in a nuclear plant
Another large project is Diapason [47, 49, 59, 63]. The goal of this project is monitoring and diagnosis of continuous dynamic systems. The application example is a pulsed column for a nuclear reprocessing plant. The columns are used to separate uranium and plutonium from fission products. They use the qualitative transfer functions approach *(see Section I)* which was devised in the framework of this project. A simulation is performed to predict the future trajectories of variables. These are then tracked against actual trajectories to perform fault detection. The fault detection procedure is presented in [59]. The system is still in prototype form but it includes a very fancy user interface.

Distillation Column
The work by Feray-Beaumont [5, 6] is in conjunction with the people working on Diapason, although this author has now moved. Hence the main focus and approaches are similar. The focus of the work is using qualitative reasoning for continuous process supervision. This work is on a distillation column. They are using the Qualitative Transfer function approach to simulation. The example given is a pilot plant distillation column with methanol and water. They show that the simulation produces a similar result to the real parameters for the top product flow. Feray-Beaumont has moved to Alcatel Alsthom Research in Marcoussis, France. The contact of the University of Newcastle is now Dr. F. Corea.

Biotechnology fermentation process
Trave-Massuyes et al [12] are working on a process supervision system for a fed-batch biotechnology fermentation system. They are using the CA-EN tool which implements a constrained influences approach [9, 11]. CA-EN is aimed at reasoning on line, to support tasks required in dynamic systems supervision such as: (1) assessing the value of non-observable variables and the current state of the system; (2) making predictions; (3) determining corrective actions in case of faulty behavior; (4) explaining the process behavior by referring to its history. CA-EN has an explicit representation of time, using on the one hand a logical clock accordingly set to the swiftness of the process, on the other hand a time management module based on time-point algebra. The CA-EN modeling involves 'q-automata' to represent the process variables together with the knowledge needed to reason about them *(see Section I)*.

Co-generation plant
Okuda and Ushio [61] have as an application a co-generation plant. This is a plant that generates heat and electricity together using a gas turbine. They are using petri net based qualitative models. Their main focus is using the petri nets and qualitative simulation together. They give an example of a hierarchical model of the plant. They then show a simulation which correctly gives the changes in the key parameters due to an increase in speed. They are interested in monitoring and diagnosis, but the current status of the project is not clear in the paper.

TIGER: Gas turbines.
The Esprit project Tiger [55, 56] is a recent project that involves Qualitative Reasoning. This is lead by Rob Milne of Intelligent Applications [54] and includes the french QR groups of Louise Trave-Massuyes of CNRS-LAAS and Laurent Zimmer of Dassault Aviation. The application focus is monitoring and diagnosis of a gas turbine. Application sites include a large industrial turbine at Exxon Chemical and a small aircraft auxiliary power unit turbine at Dassault Aviation. Qualitative simulation is being used to predict the behaviours of the turbine at start up and in response to load changes. The tool to be used is CA-EN which implements a constrained influences approache including explicite representation of causality and time. The CA-EN prediction module is foreseen to be used in a model-based framework (1) to provide the reference dynamic behavior to which observed behavior will be compared, thus allowing discrepancy detection; (3) to perform candidate generation by searching backwards in the causal dependency graph of the models; (2) to test fault candidates and proceed to their discrimination.

SEXTANT: Nuclear Power PLants
This project [22, 51] has developped a diagnosis strategy based on a combined use of numeric and QSIM-like qualitative models. Qualitative models are used to for candidate generation whereas the validation of these candidates is performed with the numeric models. The system implements a Reiter type of diagnosis algorithm. The example given is a toy example but the system is intended to be used on nuclear power plants.

QDIAG: Dynamic systems diagnosis
This project [17] uses the qualitative simulator QSIM. It uses fault models which are simulated off line. The diagnosis module then follows the trees of behaviors corresponding to the observed evolution of the system, allowing then to indicate the fault models which match the current system behavior. The system needs to be used on a real system.

Waste water treatment
Tetreault, et al. [78] are working on a waste water treatment process. The main focus of their work is on how to use temporal constraints to reduce the simulation space that results from a QSIM like simulation. They mix qualitative data with quantitative data to help reduce the simulation space. They have not developed a working system, but show how their work can be applied to the waste water treatment problem to give an accurate simulation. They have shown that the semi-qualitative/quantitative model they developed produces a similar behaviour to a numerical simulation. They are using QSIM, and only performing simulation so far.

<u>Modelling and Analysis</u>

Cooling circuit of an electrical power plant
The work by Sugaya [77] of ABB has as an application the cooling circuit for an electrical power generator. Focus is modelling and analysis. They use a device centered approach. The system is implemented in Prolog and propagates the behaviours through the device models. The results can then be viewed graphically. Typical questions they are trying to address: "What happens if this valve of a generator cooling circuit gets plugged?", "Can I turn on this breaker of a switch gear station, and if not, why not?"

Cold Trap in a Nuclear Power Plant
The application by Bourseau [8] is the cold trap in the secondary sodium circuit of a breeder nuclear power reactor. It transfers heat from the reactor to the steam generator which is transported via the sodium. It is important to keep the hydrogen levels down. They are using a Signed Directed Graph (SDG) approach. All possible behaviours of the cold trap are simulated. There are 11. The simulation does match the real behaviours. They state that there is a need to mix qualitative and quantitative methods in order to capture some order of magnitude information which may help solving undetermined influences or capture the evolution of preponderant influences over time. Their objective is mainly to provide good explanatory models which would be used as an aid to the engineer to perform an analysis. The project appears to have been a study, and is not in real use.

II.2. Engineering

<u>Monitoring and Diagnosis</u>

CRACK: Steel bridge cracks
CRACK stands for Consultant Reasoning About Cracking Knowledge [71, 72]. For many engineering problems, the engineer must use a combination of quantitative and heuristic knowledge. This group finds that Qualitative Reasoning is a good way to bridge the gap between the two. The data is often incomplete, inexact and stated in non-numeric terms. The application domain is the ability to analyse and predict failures in steel bridge beams. This has been done for two types of bridges. The goal of an application is as a consultant advisor to a bridge engineer to help him perform the needed analysis. The system has three levels; (1) A rulebased level to define problems, generate hypotheses and reach conclusions; (2) A qualitative level to construct, validate and refine models; (3) A quantitative level for numerical analysis. A library of components is used to represent a typical bridge. The primary qualitative technique is using constraints and a network of dependency relationships (normally causal relationships) between the system's state parameters (QDE-like approach). The network is used to propose possible crack progression sequences to guide a quantitative analysis. These proposed progressions are then evaluated to determine the most probable crack cause. Each step of the qualitative sequence is simulated with a numerical model. The author comments that more technical advances and a combination of techniques are needed before this will be really practical.

Hydraulic circuits.
The work by P.A. Hogan, et al, [34] is on diagnosis of faults in Hydraulic Circuits. The goal is the post event diagnosis of in-service hydraulic circuit failures. A major attraction to QR is the component model approach. A model of each component is made, primarily of the pressure levels and the flow rates. The Failure Modes and Effects Analysis (FMEA) results are used to help build the models. The diagnostic procedure tries to isolate the fault to a specific component and suggests the component failure mode. They use fault models to do this. The initial input to the program is a statement from the user of the system level failure mode to be diagnosed and an indication of where the problem was observed. The diagnosis gets information from the operator in an interactive way. Primary focus is on faults in a Hydrostatic Transmission. The simulation infers the pressure and flow information at the critical points in the system. The system seems to be applied in the research environment to one or two examples, but in the Fluid Power center.

Turbojet engines
Rajagopalan [68] has been working on the modelling of the main parameters of a turbojet engine. A causal model has been implemented to provide a simulation. The paper give examples of the effects of an increase in air speed and throttle setting, and an example of the possible paths leading to a change in thrust.

Vacuum for semi-conductor fabrication
In the paper on numerical behaviour envelopes for qualitative models by Herbert Kay et al. [39] the main focus of this work is to bound weak qualitative models with dynamic envelopes in the QSIM system. This improves the qualitative simulation. The application example is an ultra high vacuum for semi-conductor fabrication. The focus is a monitoring system to detect when the system goes out of tolerance. The system they have developed is able to detect a leak using a series of pressure measurements that simulate a gasket leak. Application is just an example, although it is robust for the example given.

Automobile screen wash system.
Hunt and Price [35, 37, 65, 66] are working on a qualitative model based diagnosis system. The work is underway. They have worked on the screen wash subsystem of a Jaguar Car. They use their own qualitative simulator, which propagates values across components based on a connectivity network. Their current project is for the electric mirror control of the car. This project is in conjunction with Jaguar and Genrad, who developed the existing Jaguar diagnosis system.

Naval diesel engine
Marchal and Camacho [52] are working on an application to a naval diesel engine supercharger system. Their main objective is to develop qualitative behaviour models of the main engine of a ship that can be used for monitoring, failure detection, diagnosis, prediction and instruction. The system is implemented in SMALLTALK. They give QSIM models of the turbocharger system. They give an example of how the system can detect a problem of the cooler becoming soiled. They also show how the qualitative model agrees with a numerical simulation. The work is continuing.

CNC machining centers
Rehbold [69] is working in the application area of diagnosis of CNC machining centers. The system is called MOLTKE. It uses component oriented models. These provide for the propagation of behaviours based on models. The system is implemented in SMALLTALK. The main focus to date is the electrical and hydraulic sub systems. They have implemented example diagnostics for these areas. They use their own style of model and propagate qualitative states. Work on the system is continuing. This is one of the more application oriented projects, but is more in the area of model based diagnosis than qualitative reasoning.

Photocopier machines
Umeda et al [84] are working on the development of machines that can continue to function even when they have a fault (fault tolerant). They combine model based diagnosis and repair with a qualitative physics based model. They give an example of the technique applied to a photocopier.

Greenhouse heating system
The work by Bradshaw and Young [13] is an example of a simple greenhouse heating system. The system is called Doris. They generate an envisionment graph of the predicted behaviour states of the represented device. These are then compared with the knowledge of purpose of the behaviour descriptions. When conflicts are detected, the system tries to identify the source of the conflict. They propagate qualitative values. Time advances only when an interesting qualitative change is made. Envisonment graph is in the style of de Kleer and Brown. Two examples are used to show the evolution of the predicted states and the detection of deviations from the simulation. For this work an envisionment is used to embody the full simulation (not shown in this paper). This is just an example of their technique, not a real application.

DIAMON: Monitoring and Diagnosis of a central heating system
Lackinger and Nejdl [46] are working in the DIAMON (Diagnosis and Monitoring Algorithm) system. It combines consistency based diagnosis with QSIM like system models. They show how the technique can be used for troubleshooting of a central heating system. The model shows the QSIM constraints between the parameters. The system is shown to identify the cause of an example fault. This is not a real application, just an example for the research.

Another central heating system
Koch's [44] application domain is also a central heating system. He is working with Landis and Gyr, one of the largest building environmental control companies. The focus is on diagnosis. He assumes that you can have the building control system perform tests to help with the diagnosis. The system is shown to work on an example of blocked dampers. The work has been conducted on a model, and not on a real building. He uses simple static qualitative models and propagation of values. The work is continuing.

Engineering Design

Air supply for space suit
Travé-Massuyès and Zimmer are working in the design of the air supply circuit for a space suit which was intended to be used with the Hermes space shuttle. They are using their own tool, SQUALE [58], which is inspired from QSIM, but has better mechanisms for constraint handling and to reduce spurious behaviours. The goal is to use the qualitative simulation to give all behaviours of the space suit system. These behaviours can then be evaluated in order to check for design problems or unwanted behaviours. A basic simulation has been implemented and the work is continuing.

Electric motors
Kiriyama, Tomiyama and Yoshikawa [41, 42, 43] are working on the design of electric motors. They use a meta model to anticipate the behaviours of the system being designed. The idea is to be able to anticipate its behaviours before the device is built or sufficient data is available for a numerical simulation. The system uses a library of components that are assembled by the designer. The designer makes a primary model, a qualitative model is then derived from this. The system is implemented in SMALLTALK. They show the primary model of the motor and the corresponding derived meta model. The meta model includes all the potential behaviours of the motor. The system can also create a dynamic model of the motor showing the different episodes from rotation. For a bad design or

problem, such as a broken coil, the system is shown to correctly predict the (incorrect) behaviour.

Mechanical Systems
Sacks and Joskowicz [73] are working on a simulation program for rigid part mechanisms. The program performs a kinematic simulation of the behaviour produced by part contacts and input motions along with a dynamic simulation of the behaviour produced by gravity, springs and friction. The program is more efficient and informative than traditional simulators. It covers more mechanisms than do previous model based simulators, generate fuller behavioural descriptions, and exploits kinematics more fully. They have demonstrated that the simulation algorithm captures the workings of most mechanical mechanisms by surveying 2,500 mechanisms from an engineering encyclopedia. In their paper they give examples of a feeder mechanism, brake shoe and a rim lock.

Mechanical systems
Yannou [89] proposes a design tool called QDES based on the model envisionment and the representation of functional requirements related by design histories. The system detects the intersections between the expected behaviors (requirements) and the possible behaviors (envisionment).

Design of automatic process discrete control systems
Valisou in Finland [85, 86] is focused on the design of automatic process plant discrete control systems and to help plan actions to take when the plant is operating. They have developed a prototype tool called ISIR. The work uses an approach similar to QSIM, and is implemented with constraint logic programming. An example is given of a power plant feed water system. The work is continuing,

II.3. Ecology

Prediction in plant physiology
The work by Rickel and Porter [79] is based on QSIM. The focus of the work is to help predict the behaviours that would result from a hypothetical situation (a prediction question). The domain of interest is in plant physiology. A typical question might be : "How would a decreasing amount of soil water affect plant size and growth rat?" From the influence network , it can be seen that this would result in an increase in size, since soil-water-amount ->Q+ water-uptake-rate ->I+ apoplast-water-amount ->Q+ symplast-water-amount ->Q+ turgor-pressure ->Q+ growth-rate ->I+ size. This is one path resulting from the model and its qualitative relationships.

Other projects
The paper by Cooke and Hunt [18] gives short descriptions of eight projects involving qualitative reasoning in the biological and ecological domains. For now, only a summary of the projects is included: (1) Gaglio models the cell cycle and the effects of anti-proliferative drugs on it; (2) University of Texas at Austin is developing an intelligent tutor for first degree level biology students; (3) Hunt and Cooke are developing QRP, Qualitative Reasoning for Plants to analyse the potential effects of mutant strains of plants and the potential effects of external environmental changes; (4) Rogoyski has developed a qualitative model of the drop rate of apples throughout the growing season; (5) Schmoldt has developed a qualitative model based simulation of the response of a Ponderosa Pine tree to stress; (6) Guerrin is working on a qualitative model of an aquatic ecosystem of fish ponds which are fed on phytoplankton and zooplankton [32, 33]; (7) Plant and Loomis are developing a qualitative simulation based model to be part of an integrated decision support system for crop management; (8) Saarenmaa has developed a qualitative model of animal-habitat interaction. In particular the model is of the interaction of moose and forest plantations in Scandinavia.

II. 4. Electronic Circuits

Diagnosis: OR gate
The application example in Mozetic [60] is diagnosis of electronic circuits. His real focus is the combination of qualitative and quantitative simulation. The numeric model is used to discriminate between competing qualitative hypotheses. He gives an example of an OR gate at the level of three npn transistors. He derives the qualitative model from the numerical one. He uses fault models to help with the diagnosis. He finds the fault models at the qualitative level and then uses the numeric level to verify them. This is an example to show his technique, not a real application.

Diagnosis: Analog circuits
Dague et al [19] are also working on troubleshooting of complex analog circuits. The real focus is on diagnosis using relative order of magnitude reasoning *(see Section 1)*. The system is called DEDALE. DEDALE was tested on a real size application in a factory environment. They state that it can find 75% of failures. These are the class where a fault leads to a significant change of behaviour. The other 25% do not cause significant changes of behaviour, but can be found by other means. Neither of the lead authors are still at IBM. This is an example, but the work has been done with Electronique Serge Dassault who continued work in this area and now commercialises a product called DIAGMASTER implementing this research.

II.5. Business and Commerce

Diagnosis of Business Performance
Daniels and Feelders [21, 22, 23] are working on model based diagnosis of business performance. Their application is diagnosis of a business performance. For example to answer the question of "why did sales go down?" They give an example of a qualitative model of the sales volume, price and cash position of a company. They show how this can provide explanations for changes such as a decrease in sales. Their approach is basically one of causal and constraint relations rather than simulation. They give an example that traces why a decrease in advertising, leads to a decrease in sales, which causes assests to decrease, which is a business problem. The system is implemented in the constraint logic programming language CHIP. They show how they are using a standard diagnosis architecture. The system tries to generate all explanatory sequences for a query. The

system seems to be a development prototype, although a support tool for loan evaluation by banks is being investigated. The work is continuing in conjunction with the AMRO bank in the Netherlands.

Prediction: market exchanges
For Farley and Lin [30] the application area is market based modelling using qualitative simulation. The focus is the commodity exchange. They use the qualitative simulation to produce predictions of the effects of changes in the demand, supply and price. They use a QSIM approach. They give several models of the influences of drinks commodities. The current status of the project is not clear from the paper.

Prediction: business cash flow
Bailey et al. [1] are working to support business executives in planning, controlling and business evaluation tasks. They are using QSIM. They give an example of a qualitative model of a business cash flow. Bailey [2, 3] gives more detailed examples. The models and simulation is designed to help auditors. In order to diagnose problems, they use a fault model approach. The work is continuing but not in usage yet.

II. 6. Medical

Explanation of electrocardiograms.
For Kirby and Hunter [38, 40] the application area is the human heart. Although Hunter works in the medical domain, this system has not gone further. He gives an indication of how qualitative simulation can be used to explain electrocardiograms in terms of the underlying physical processes. The technical approach is to use a QSIM like strategy with temporal constraints. The model is shown to provide accurate predictions of the ECG for the selected examples.

KARDIO: interpretation of ECGs
The KARDIO system by Bratko [14] is probably the most advanced application of qualitative reasoning. The application focus is the interpretation of ECGs for the human heart. The task was to recognise arrhythmias. Qualitative models are used to generate the behaviours of the heart. A rule induction system is then used to create a 'rulebase' for diagnosis. The system proved very accurate in early trials both at recognising and predicting what an arrhythmia would appear like in the ECG. It is understood that some of the diagnosis is now being embedded in a system called Intelligent Pacemaker by a company Telectronics in Australia.

Diagnosis: cardiovascular system
Downing [26] is working on qualitative model based diagnosis using the cardiovascular system. He combines a qualitative causal network with model based diagnosis techniques based on GDE and SHERLOCK. The network he has can help to explain some example faults. The work is just theoretical and not being applied to a real medical situation.

Diagnosis: thyroid stimulating immunoglobulin
For Dugerdil and Guillod [28] the application area is medical with a focus on diagnosis. Note that the second author works at a hospital. The main focus of their work is a qualitative diagnosis system, and an architectural tool is proposed. They give a model of a thyroid stimulating immunoglobulin. They use three values for the simulation (increasing, normal, decreasing) and propagate the influences. The system seems to work for the example given in the paper. The current status of the project is not clear.

Explanation: metastatic cancer causes brain tumor
Parsons and Fox [62] report on more work in the medical domain. The work is part of the Esprit project DRUMS. They give an example of how metastatic cancer can cause a brain tumor. They are using an extended version of Williams' Q1 approach. They also give an example of gastroenterological complaints such as uclers and gall stones. The approach is shown to work on the two examples given. The work is continuing.

II.7. Other areas

ELSA: Avalanche path analysis
Buisson [15] developed a system called ELSA for avalanche path analysis. It is written in SHIRKA, an object oriented language. The system combined heuristic rules with qualitative spatial simulation and numerical simulation. The system is designed to be used by a snow specialist to examine scenarios of snow release. The key calculation is the stopping distance. The system took four years to develop and is operational. Several examples are given in the paper.

Prediction: urban traffic control
The application for Toledo et al [79] is to urban traffic control. It aims at predicting future conflictive situations as well as at detecting abnormal situations. The main focus is a qualitative simulator with temporal aspects. The system is implemented in PROLOG. A real zone of the city of Valencia covering six intersections was used as a test case. They conclude that the simulation is good enough. This work is part of the ESPRIT project EQUATOR.

Geoprospective analysis
The project PROSPECT [25] aims at buiding evolution scenarios for geaoprospective analysis. They use a causal model in which they propagate histories (piecewise linear temporal functions) by using the operators associated to every edge of the graph. The model is process oriented.

Even more!
The paper of Hunt et al [36] provides a summary of several more applications using qualitative reasoning. Although over 20 applications are listed, some of these are more properly considered model based diagnosis tools, rather than specific applications (for example, GDE and SHERLOCK).

Conclusion

This paper has given a summary of recent application oriented work. Although there is a long list of projects, the majority are research projects with realistic examples and have no short term intention of building a usable application. There are a few applications under way, however, very few systems are in regular use.

It is interesting to note that most people doing application oriented work cite the need for the integration of qualitative and quantitative models. Most also comment that current simulation techniques do need improvement before being able to deal with the real problems being tackled. In other words it appears that a consensus is emerging of areas for further work and integration with other techniques that will be needed to make real, usable daily, qualitative reasoning based applications.

References

[1] Bailey A., Kaing Y., Kuipers B., Whinston A., *Analystical Procedures and Qualitative Reasoning in Auditing*. Applications in Management Science, (JAI Press, 1990)

[2] Bailey A., Kaing Y., Kuipers B., Whinston A., *Qualitative Reasoning in Auditing" in Yuji Ijiri* (ed.), Creative and Innovative Approaches to the Science of Management, (1991).

[3] Bailey D.A., Kiang Y., Kuipers B., Whinston B.A., *A Theoretical Framework for Modeling Executive Support Systems: A Qualitative and Causal Reasoning Approach*. Dept. of Accounting, College of Business and Public Administration, University of Arizona, USA. & Dept. of Management Structure and Information Systems, University of Texas, Austin, TEXAS. & Dept. of Computer Science of Texas, Austin, TEXAS, & Dept. of Management Science and Information Systems, University of Texas, Austin, TEXAS. Decision Support Systems and Qualitative Reasoning, Toulouse 1991.

[4] Beaumont-Féray S., *Modèle Qualitatif de Comportement pour un Système d'Aide à la Supervision des Procédés*. Thèse de Doctorat INPG, Grenoble, 1989.

[5] Beaumont-Féray S., *Qualitative Model-Based Reasoning: An Application to Distillation Process*. Dept. of Chemical and Process Engineering, University of Newcastle, Newcastle-Upon-Tine, UK. Decision Support Systems and Qualitative Reasoning, Toulouse 1991.

[6] Beaumont-Féray S., Corea F.M.R., Tham M.T., Morris A.J., *Qualitative Modelling of Distillation Columns*. Department of Chemical and Process Engineering, University of Newcastle, Newcastle-upon-Tyne, UK, & Process Control Lab, ICPI-Lyon, Lyon, (France). IFAC, Toulouse, 1991

[7] Bertin A., Gallanti M., Stefanini A., Tornielle G., *Diagnostic Reasoning Based on Dependency Analysis*. CISE SpA, Milan, (Italy).

[8] Bourseau P., Brilloit P., Latge C., Muratet G., *Qualitative Analysis of a Complex Chemical Plant: Application to a Cold Trap of a Nuclear Power Reactor*. UPR CNRS 1311, University Paris Nord, (France) & Commissariat a l'Energie Atomique, (France), European Workshop on QR, January 91, (Italy).

[9] Bousson K., Travé-Massuyès, L., *A Computational Causal Model for Process Supervision..* IFAC International Symposium on "Artificial Intelligence in Real-Time Control", Delft (The Netherlands), 1992, pp. 183-189.

[10] Bousson K., Travé-Massuyès. L., *Formalizing Expertise: Qualitative Operators*. ECAI-92, Vienna (Austria), 1992, pp. 694-698.

[11] Bousson K., Travé-Massuyès L., (1993). *Fuzzy Causal Simulation in Process Engineering*. IJCAI'93, Chambéry (France).

[12] Bousson K., Guerrin F, Travé-Massuyès L., (1993). Qualitative Prediction and Interpretation for Bioprocess Supervision. Tooldiag'93 Int. Conf., Toulouse, (France).

[13] Bradshaw J.A., Young R.M. *Integrating Knowledge of Purpose and Knowledge of Structure for Design Evaluation*. Computer Laboratory, University of Cambridge, Cambridge & Applied Psychology Unit, Cambridge. European Workshop on QR, January 91, (Italy).

[14] Bratko I., Mozetic I., Lavrac N., KARDIO: *A Study in Deep and Qualitative Knowledge for Expert Systems*. The MIT Press, Cambridge, Massachusetts, London, (England), 1989.

[15] Buisson L., *Qualitative Reasoning and Decision Making in Avalanche Path Analysis*; The ELSA System. Laboratoire ARTEMIS/IMAG, Greno-ble, Cedex, (France). Decision Support Systems and Qualitative Reasoning, Toulouse 1991.

[16] Caloud P., *Raisonnement Qualitatif: Application à l'aide à la Supervision des Procédés Continus*, Thèse de Doctorat de l'INPG, 1988.

[17] Charles A., (1992). *Aide à la Détection d'Anomalies de Fonctionnement des Systèmes Dynamiques: Une Approche fondée sur des Modèles Qualitatifs et Quantitatifs*. Thèse de l'Université Technologique de Compiègne (France) (in French).

[18] Cooke D.E., Hunt J.E., *Physiological and Ecological Applications of Qualitative Modelling. Artificial Intelligence and Robotics* Research Group, Department of Computer Science, University of Wales, Abertstwyth, Dyfed.

[19] Dague Ph., Raiman O., Deves Ph., *Troubleshooting: When Modeling is the Trouble* . IBM Scientific Center, Paris, FRANCE & Electronique Serge Dassault, France. AAAI'87.

[20] Dague P., Order of magnitude revisited, *Qualitative Physics Workshop*, Paris, France, 1988.

[21] Daniels H.A.M., Feelders, A.J., *Model-Based Diagnosis of Business Performance*. Tilburg University, Institute for Language Technology and AI, NETHERLANDS. Avignon 90.

[22] Daniels H.A.M., Feelders A.J., *Model-Based Diagnosis of Business Performance: A Constraint Logic Programming Approach*. Tilburg University, Institute for Language Technology and AI, Netherlands. European Computer-Industry Research Centre GmbH, West Germany. Proceedings of Computing Science in the Netherlands Stichting Matematisch Centre, Amsterdam 1990.

[23]Daniels H.A.M., Feelders A.J., *Combining Qualitative and Quantitative Methods for Model-Based Diagnosis of Firms*. Institute for Language Technology and AI, Tilburg University, NETHERLANDS. Decision Support Systems and Qualitative Reasoning, Toulouse 1991.

[24] De Kleer J., Brown J.S., A Qualitative Physics based on confluences, *Artificial Intelligence Journal, Vol. 24*, 1984, 7-83.

[25] Djerroud A., Rousset M.C., Godefroy P., Applying Artificial Intelligence Techniques to Geoforecasting. PROSPECT: a simulator of changes affecting radioactive-waste disposal sites, 5th International Workshop on Applying Artificial Intelligence Techniques in Seismo-ogy and Engineering Seismology, Luxembourg, Mars 1992.

[26] Downing K., *Model-Based Diagnosis of Qualitative Physiological Models*. IDA, Linko-ping University, Sweden. European Workshop on QR, January 91, Italy.

[27] Dubois D., Prade H., *Order of magnitude rea-soning with fuzzy relations, Revue d'Intelligence Artificielle, Vol. 3, no.4*, 1989, 69-94.

[28] Dugerdil Ph., Guillod J., *Deep Model Reasoning in a Medical Expert System*. Institut de Mathematiques et Informatique, Universite de Neuchatel, Switzerland & Hopital des Cadolles, Service de Medicine, Switzerland. Avignon 90.

[29] Evrard J.M., Galperin A., Thomas J.B., (1987). *Interprétation en Ligne de Processus Physiques pour la Conduite d'Installations Industrielles*. Rapport Interne DEMT/89/285, SERMA/LETR /89/1114 (confidential).

[30] Farley A., Lin K.P., *Qualitative Reasoning in Microeconomics: An Example*. Computer Science Dept., University of Oregon, OR, USA, & Economics Department, Portland State University, OR, USA. Decision Support Systems and Qualitative Reasoning, Toulouse 1991.

[31] Fouché P.,*Vers une Unification des Méthodes de Simulation Qualitative*. Thèse de l'Université Technologique de Compiègne, 1992.

[32] Guerrin F., *Interpretation of measurements, analyses and observations in partially-known processes*. Workshop Notes from the Ninth National Conference on Artificial Intelligence (AAAI-91), Model-Based Reasoning, Anaheim (CA, USA), 1991.

[33] Guerrin F., *Qualitative reasoning about an eco-logical process: interpretation in hydroecology*. Ecological Modelling, 59(3-4), pp. 165-201, 1991.

[34] Hogan P.A., Burrows C.R., Edge K.A., Woollons D.J., Atkinson R.M., *A System For Diagnosing Faults in Hydraulic Circuits Based on Qualitative Models of Component Beha-viours*. Fluid Power Centre, University of Bath, & Dept. of Engineering Science, Exeter University. Safeprocess 91.

[35] Hunt J., Price C., *Towards a Generic, Qualitative-Based Diagnostic Architecture* . Dept. of Computer Science, University College of Wales, Aberystwyth, Dyfed. Avignon 89.

[36] Hunt J., Lee M.H., Price C.J., *Applications of Qualitative Model-Based Reasoning*. AI and Robotics Research Group, Dept. of Computer Science, University of Wales, Aberystwyth, UK.

[37] Hunt J., Price C., *An Augmented Model-Based Diagnostic System Exploiting Diagnostic and Domain Knowledge*. Dept. of Computer Science, University College of Wales, Aberys-twyth, DYFED. BCS Expert Systems'91, London.

[38] Hunter J., Kirby I, Gotts N., *Using Quantitative and Qualitative Constraints in Models of Cardiac Electrophysiology*. Dept. of Computing Science, University of Aberdeen, ABERDEEN. European Workshop on QR, January 91, Italy.

[39] Kay H., Kuipers B., *Numerical Behavior Envelopes for Qualitative Models*. Dept. of Computer Sciences, University of Texas at Austin, TEXAS, USA. QR'92.

[40] Kirby I., Hunter J., *.Further Progress in Qualitative Modelling of Cardiac Electro-physiology*. Dept. of Computing Science, University of Aberdeen, ABERDEEN. QR 91 Texas.

[41] Kiriyama T., Tomiyama T., Yoshikawa H., *Qualitative Reasoning and Conceptual Design with Physical Features*. Dept. of Precision Machinery Engineering, The University of Tokyo, Tokyo, JAPAN. QR'91.

[42] Kiriyama T., Tomiyama T., Yoshikawa H., *The Use of Qualitative Physics For Integrated Design Object Modeling*. Department of Precision Machinery Engineering, University of Tokyo, JAPAN. The American Society of Mechanical Engineers, Volume 31, Design Theory and Methodology - DTM'91.

[43] Kiriyama, Takashi., Tomiyama, Tetsuo., & Yoshikawa, Hiroyuki. *Model Generation in Design. Dept. of Precision Machinery Engineering*, The University of Tokyo, JAPAN. QR 91 Texas.

[44] Koch G.G., *Knowledge-Based Co-ordination of Qualitative On-Line Diagnostic Test*. Dept. of Automatic Control, Swiss Federal Institute of Technology, Zurich, Switzerland. SICICA'92.

[45] Kuipers B.J., Qualitative simulation, *Artificial Intelligence, 29*, 1986, 289-338.

[46] Lackinger F., Nejdl W., *Integrating Model-Based Monitoring and Diagnosis of Complex Dynamic Systems*. Christian Doppler Laboratory for Expert Systems, Technical University of Vienna, AUSTRIA. QR 91 Texas.

[47] Leyval L., Gentil S., *On-Line Event Based Simulation Through A Casual Graph.*. Commissariat à l'Energie Atomique, Labora-toire d'Informatique Appliquee, Cedex, Fance & LAG-ENSIEG, Cedex, France. Decision Support and Qualitative Reasoning, Toulouse 1991.

[48] Leyval L., (1991). *Raisonnement causal pour la simulation de procédés industriels continus*. Thèse de doctorat de l'Université de l'Institut Polytechnique de Grenoble.

[49] Leyval L., Ledoux A., *Qualitative Simulation for Supervision of a Nuclear Reprocessing Plant*. Commissariat a l'Energie Atomique, CEN VALRHO - Marcoule, Cedex, France. Safeprocess 91.

[50] Leitch R., Freitag H., Struss P., Tornielle G., *ARTIST: A Methodological Approach to Specifying Model Based Diagnostic Systems*. Intelligent Automation Laboratory, Heriot-Watt University, EDINBURGH & Advanced Reasoning Methods, Siemens AG, Munich, GERMANY & Artificial Intelligence Section, CISE S.p.A., Segrate, Milano, ITALY. Milan Applications Conference, October 1991.

[51] Lucas B., Evrard J.M., (1993). An improved Diagnosis Method using a mixed Model. Tooldiag'93, Toulouse (à paraitre).

[52] Marchal J.M., Camacho E.F., *Qualitative Supervision of Naval Diesel Engine Turbo-charger Systems*. University of Cadiz, SPAIN. University of Sevilla, Spain. SICICA'92.

[53] Mavrovouniotis M.L., Stephanopoulos G., Reasoning with order of magnitude and approximate relations, *AAAI-87*, Seattle, USA, 1987.

[54] Milne R., Petroleum Applications: *How Do We Realise The Potential?* Intelligent Applications Ltd, Kirkton Business Centre, Livingston Village, SCOTLAND. *Revue de l'Institut Francais du Pétrole*, Vol. 47, No. 3. May-June 1992.

[55] Milne R., *On-Line Diagnostic Expert System For Gas Turbines*. Intelligent Applications Ltd, Kirkton Business Centre, Livingston Village, SCOTLAND. 4th International Profitable Condition Monitoring Conference, Stratford-upon-Avon, UK, 1992.

[56] Milne R., Travé-Massuyès L., (1993). Real Time Model Based Diagnosis of Gas Turbines. AIENG'93 Int. Conf., Toulouse, France.

[57] Missier A., Piera N., Travé-Massuyès L., Order of magnitude qualitative algebras: a survey, *Revue d'Intelligence Artificielle, Vol. 3, no.4*, 1989, 95-109.

[58] Missier A., Zimmer L., Jezequel L.P., Travé-Massuyès L., *The Qualitative Simulator SQUALE*. TOOLDIAG'93, Toulouse, France, April 93.

[59] Montmain J., Gentil S., *Interprétation Qualitative pour le diagnostic en ligne*. Commissariat à l'Energie Atomique, Laboratoire d'Informatique Appliquee, Cedex, France. Laboratoire d'Automatique de Grenoble, Domaine Universitaire, Cedex, France. Diagnostic et Surete de Functionnement.

[60] Mozetic I., Holzbaur C., *Integrating Qualitative and Numerical Models within Constraint Logic Programming* .Austrian Research Institute for AI & Austrian Research Institute for AI, and Dept. of Medial Cybernetics and AI, University of Vienna, AUSTRIA. European Workshop on QR, January 91, Italy.

[61] Okuda K., Ushio T., *Hierarchical Qualitative Simulation for Large Scale Dynamical Systems*. Fundamental Research Labs, Osaka Gas Co Ltd, Konohana, Osaka, JAPAN & School of Home Economics, Kobe College, JAPAN. AI in Engineering'91, Oxford, July, 1991.

[62] Parsons S., Fox J., *Qualitative and Interval Algebras for Robust Decision Making Under Uncertainty*. Dept. of Electronic Engineering, Queens Mary and Westfield College, LONDON & Biomedical Computing Unit, Imperial Cancer Research Fund, LONDON. Decision Support Systems and Qualitative Reasoning, Toulouse 1991.

[63] Penalva J.M., Coudouneau L., Leyval L., Montmain J., *DIAPASON: Un Système d'Aide a la Supervision*. Centre d'Etudes Nucleaires de la Vallee du Rhone, FRANCE. Avignon 91.

[64] Piera N., Sanchez M., Travé-Massuyès L., *Qualitative Operators for Order of Magnitude Calculus : Robustness and Precision*, In: 13th IMACS World Congress, Dublin, Ireland, 1991.

[65] Price C., Hunt J., *Using Qualitative Reasoning to Build Diagnostic Expert Systems*. Dept. of Computer Science, University College of Wales, Aberystwyth, DYFED. Avignon'89.

[66] Price C., Hunt J., *Augmenting Qualitative Diagnosis*. Dept. of Computer Science, University College of Wales, Aberystwyth, DYFED. MBD 91

[67] Raiman O., Order of magnitude reasoning, *Fifth National Conference on Artificial Intelligence (AAAI-1986)*, Philadelphia, USA.

[68] Rajagopalan R., *Qualitative Modeling in the Turbojet Engine Domain*. Co-ordinated Science Laboratory, University of Illinois at Urbana-Champaign, Illinois, USA. AAAI, 1984.

[69] Rehbold R., *Model-Based Knowledge Acquisition from Structure Descriptions in a Technical Diagnosis Domain*. University of Kaiserslautern, Dept. of Computer Science. GERMANY. Avignon 89.

[70] Rickel J., Porter B., *Automated Modeling for Answering Prediction Questions: Exploiting Interaction Paths*. Dept. of Computer Science, University of Texas, TEXAS, USA. QR'92 Edinburgh.

[71] Roddis K.W.M., Martin L.J., *Qualitative Reasoning About Steel Bridge Fatigue and Fracture*. Dept. of Civil Engineering, University of Kansas, USA. QR 91 Texas.

[72] Roddis K.W.M., Martin J.L., *CRACK: Qualitative Reasoning About Fatigue and Fracture in Steel Bridges* . IEEE Expert, Volume 7, Number 4, 1992.

[73] Sack E., Joskowicz L., *Model-Based Kinematic Simulation*, QR'92, Edinburgh 1992.

[74] Shen Q., Leitch R., *A Semi-Quantitative Extension to Qualitative Simulation*. Heriot-Watt University, Intelligent Automation Laboratory, Electrical & Electronic Engineering Dept. EDINBURGH. *Avignon'90, Conf. on Second Generation Expert Systems*, Avignon, France, 1990.

[75] Struss P., *Mathematical Aspects of Qualitative Reasoning*, Artificial Intelligence in Engineering, Volume 3, Number 3, 1988.

[76] Shen Q., Leitch R., *Synchronised Qualitative Simulation in Diagnosis*. Intelligent Automation Laboratory of Electrical & Electronic Engineering, Heriot-Watt University, EDINBURGH. QR 91 Texas.

[77] Sugaya H., *Qualitative Modelling for Industrial Applications*. Asea Brown Boveri Corporate Research, Knowledge Systems Group, SWITZERLAND. Avignon'89.

[78] Tetreault M., Marcos B., Lapointe J., *Temporal Duration Reasoning in Qualitative Simulation*. Artificial Intelligence in Engineering, Volume 7, Number 4, 1992.

[79] Toledo F., Moreno S., Rosich F., Martin G., *Qualitative Simulation in Urban Traffic Control: Implementation of Temporal Features*. Dept. de Informatica y Electronica, Univesitat de Valencia, Valencia, SPAIN. Decision Support Systems and Qualitative Reasoning, Toulouse 1991.

[80] Travé-Massuyès L., Dormoy J.L. *Qualitative Calculus and Applications in IMACS Transactions on Scientific Computing'88, vol.2 : Artificial Intelligence and Expert Systems in Scientific Computing*, J.C. Baltzer AG, 1989.

[81] Travé-Massuyès L., Piera N., Order of magnitude models as qualitative algebras, *11ème IJCAI, Detroit*, USA, 1989.
[82] Travé-Massuyès L., Missier A., Piera N., Qualitative models for automatic control process supervision, *IFAC World Congress, Tallinn*, 1990.
[83] Travé-Massuyès L., *Qualitative Reasoning Over Time: History and Current Prospects.*, LAAS-CNRS, Toulouse, France. The Knowledge Engineering Review, Vol 7, No. 1, 1992.
[84] Umeda Y., Tomiyama T., Yoshikawa H., *A Design Methodology For A Self-Maintenance Machine*. Dept. of Precision Machinery Engineering, University of Tokyo, JAPAN. The American Society of Mechanical Engineers, Design Theory and Methodology - DTM'91.
[85] Valisuo H., *Model Based Reasoning in the Design of Discrete-Event Control*. VTT, Laboratory of Electrical and Automation Engineering, FINLAND. New Directions in Artificial Intelligence, Volume 3, Finnish Artificial Intelligence Conference, 1992.
[86] Valisuo H., *Computer-Aided Design of Plant Automatics*. VTT, Laboratory of Electrical and Automation Engineering, FINLAND. Joint Finnish/Russian Symposium on Computer Aided Control Engineering.
[87] Vescovi M., La représentation des connaissances et le raisonnement sur les systèmes physiques. Thèse de doctorat de l'Université de Savoie, 1991.
[88] Vescovi M., Simulating and explaining the behavior of physical systems described by structural equations, *IMACS International Workshop sur Les Systèmes d'Aide à la Décision et le Raisonnement Qualitatif*, Toulouse, France, 1991.
[89] Yannou B., *Qualitative Design with Envisionment*. Ecole Centrale de Paris, France. QR'93 Workshop, Orcas Island, WA, USA, 1993.