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Application oriented qualitative reasoning

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Abstract

The techniques of qualitative reasoning are now becoming sufficiently mature to be applied to real world problems. In order to better understand which techniques are being used successfully for real world applications, and which application areas can be suitably addressed using qualitative reasoning techniques, it is helpful to have a summary of what application oriented work has been done to date. This helps to provide a picture of the application areas in which the techniques are being applied, and who is working in each application domain. In this paper, we summarize over 40 relevant projects.

1 Introduction

Qualitative reasoning (QR) has been a very active research field of Artificial Intelligence for more than a decade (AI Journal, 1984, 1991). Motivated by the objective of building an artificial engineer, QR aims at automating several types of reasoning that engineers, technicians and scientists perform when understanding, explaining, designing, or diagnosing physical systems.

QR has a considerable impact not only on AI as a whole by suggesting a novel view of how to approach the physical world, but also on the many engineering domains which benefit from the new solutions arising from QR techniques (de Kleer *et al.*, 1993).

From the beginning of the field, work in 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. To do so, it is helpful to have a summary of what application oriented work has been done to date. This helps to provide a picture of the application areas in which 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 summarized, there is only a short description of each project.

What is "application oriented" work? For the purposes of this summary, it is reports of work in progress or recently completed where the examples given are more than toy or generic examples, such as 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 not go beyond the laboratory work of a research group. However, 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 industrial QR systems, or systems that are designed for day to day 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 primary emphasis of this survey is work in Europe. This is not intended to be an exhaustive survey, but covers most of the major projects.

The first part of this paper overviews the important mathematical aspects related to qualitative reasoning and provides a brief overview of the most common formalisms for representing physical systems from a structural and behavioural point of view, with the related references.

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, which are listed in the bibliography.

2 Some representation formalisms and algorithms used in QR

It is widely agreed in the QR community that the reasoning processes of engineers and scientist are generally supported by structural and behavioural models of the physical system. This section presents some of the important mathematical aspects related to qualitative reasoning and provides a brief overview of the most common formalisms for representing physical systems from a structural and behavioural point of view (Travé-Massuyès. 1992).

2.1 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 a symbolic ordered set, which is called the *quantity space* of the variable. As $\Re$ is often referred to as the value of physical variables, the quantity space is generally a partition of the real line in which a qualitative value corresponds to a subset of $\Re$ (for instance, see Fig. 1). 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 viewed in an abstraction continuum going from the highest level of abstraction (sign algebra) to the lowest one (interval algebra which allows representing even real numbers).

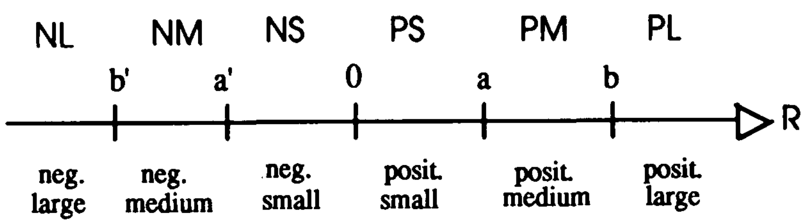


Figure 1 A special partition of the real line

The important concept of *qualitative equality*, $\approx$, is generally understood as the *possibility of being equal*. In other words, two qualitative values are qualitatively equal if the subset of the reals that they represent have a non empty intersection. An axiomatisation of the qualitative equality was provided in (Travé-Massuyès and Piera, 1989). A major difficulty in the qualitative calculus lies in the fact that *qualitative equality is not transitive*.

2.1.1 Sign algebra

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 the undetermined sign. ? is necessary to obtain the closure of the sum and product operators. Operators are defined in a trivial way, e.g. $+\oplus+ = +, +\oplus- = ?, \ldots$

Although the roughness of the sign partition introduces 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 the qualitative calculus rather feasible (Struss, 1988). In particular, a qualitative resolution rule has been proved (Travé-Massuyès and Dormoy, 1989). Sign algebra is one of the most often used tools in qualitative reasoning.

2.1.2. Order of magnitude qualitative algebras

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 (Travé-Massuyès and Piera, 1989). These algebras convey quantitative information as the partition of $\mathfrak{R}$ is specified by numerical boundaries. The calculus then often requires explicit reference to real numbers.

This leads to the fundamental difference relative to sign algebra: a given symbolic quantity space now corresponds to an infinity of partitions of $\mathfrak{R}$ (related to the choice of numerical boundaries, a, b, a', b', for Figure 1). Consequently, symbolic tables for $\oplus$ and $\otimes$ 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 Figure 1, and robustness and precision of the sum and product tables have been studied (Piera *et al.*, 1991).

The order of magnitude qualitative algebras do not have the same interesting properties as sign algebra so that qualitative calculus is more difficult (Missier *et al.*, 1989; Struss, 1988). Besides non transitivity of the qualitative equality $\approx$, two other significant problems are encountered: *lack of associativity* of operators for $\oplus$ and $\otimes$ and *lack of distributivity*. In other words, the same arithmetic expression yields different results depending on the processing sequence. It is guaranteed that the results are always qualitatively equal, but this means that the solution may not be "minimal". In a simulation framework, this is one of the causes of spurious behaviours. In this case however, spurious behaviours are a subset of those which would be generated with sign algebra. Particular partitions can be proposed to overcome some of these problems (Travé-Massuyè *et al.*, 1990). On the other hand, preliminary discussions on the advantages and disadvantages of fuzzy partitions can be found in Dubois and Prade (1989).

2.2. Some examples of QR approaches

2.2.1 The confluences approach

Confluences are multivariable linear equations relating variable variations in a quasi-static approach and whose parameters take qualitative values. The term *confluence* was introduced by de Kleer and Brown (1984).

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 component 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 of equilibrium for instance. A system may have several modes, each one described by a set of confluences.

The approach of de Kleer and Brown provides an envisionment. Roughly, and without considering *several* modes, the first step consists of solving the confluences in the sign algebra with qualitative calculus (Travé-Massuyès and Dormoy, 1989) or constraint propagation (de Kleer and Brown, 1984) techniques. The solutions represent the admissible states of the system, and 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 behaviours appear as sequences of states which the system may go through from a given initial state node.

2.2.2 The qualitative process theory approach

This approach proposed by Forbus (1984) is centred on the concept of *process*. The description of a physical system indeed relies on identifying all the processes which occur within a physical system (like fluid flowing process, a heat generation process, etc.) and on successively determining which are active and make the system evolve.

A *process* is associated to a set of objects or *individual views* (IV), and it specifies their mutual influences in terms of the possible evolution of their parameters. The objects correspond to the physical elementary components of the physical system (e.g., a valve, a pipe, etc.), they may be grouped in an individual view which has four attributes:

- the individuals (objects or other IV) composing the IV;
- pre-conditions for the existence of the IV;
- conditions on the quantities;
- functional relations, called *indirect influences*, existing among the quantities when the IV conditions and pre-conditions are satisfied. These relations, denoted $f\,\alpha Q+\,g$ and $f\,\alpha Q-\,g$, state the sign of the partial derivative of a quantity f with respect to a quantity g.

A process additionally includes the representation of *direct influences*, denoted I+ (f,g) and I− (f,g), which stand for the derivation operation.

In Forbus' approach, a quantity can change, if and only if it is influenced directly or indirectly by a process.

2.2.3 The qualitative differential equations (QDE) approach

This approach was proposed by Kuipers (1986) and implemented in the system QSIM. A physical system is described by three types of elements: variables, constraints and operating regions. Operating regions define the different modes of the system. In a different way than the confluence approach, variables may have a different quality space. The constraints specify the relations between variables within a given operating region. Basically, the relations between variables are expressed by using the following operators (Kuipers, 1986):

- 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 QSIM simulation algorithm starts from an admissible initial state, the algorithm finds all possible successor states by using a table of authorised transitions. This table relies on the properties of continuously differentiable functions (notice the overlap with the de Kleer and Brown approach). The second step uses the QDE model to filter out states which are inconsistent with some constraint in the QDE. Because of the inaccuracy inherent in the model, there are generally several admissible successor states. Hence simulation provides a tree whose branches represent possible behaviours in terms of sequences of states. Numerous improvements have been added to the algorithm in the initial version (Fouché, 1992).

2.2.4 The relative order of magnitude approach

This approach is based on qualitatively comparing entities without referring 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 Raiman (1986). *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 through the constraint network expressing the relationships between variables. This formalism was devised for reasoning about analog electronic circuits.

Other formalisms, derived from *FOG*, were later proposed to provide solutions to some unsolved problems (Dague, 1988; Dubois and Prade, 1989; Mavrovouniotis and Stephanopoulos, 1987). In particular, major issues were to make the system accept purely numerical values, and to provide a satisfactory answer to the problem of non real transitivity of operators and to obtain results valid in the real world.

2.2.5 The qualitative transfer functions (or propagation functions) approach

As opposed to the three approaches presented above, which do not presume causality, this approach proposes an explicit representation of causal relations. This system model is supported by an oriented graph in which the nodes represent the variables of the system and the edges represent the influences from one variable to another. This formalism is inspired from automatic control theory in which transfer functions are used to relate the output variables of linear systems to input variable changes. Given a temporal function as input, they associate another temporal function as output (Beaumont-Foray, 1989; Caloud, 1988; Leyval, 1991).

In a similar way, *qualitative transfer functions* (QTF) define a behavioural constraint between input and output variables and capture the type of constraint as well as experimental data like qualitative value of grain, 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 to another *QTF*, which makes it possible to propagate a temporal function through a cascade or a network of *QTFs*. This propagation procedure is at the basis of the simulation algorithm (Leyval and Gentil, 1991).

Propagation functions (PF) introduced by Vescovi (1991a, b) also define behavioural 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 the step signal (called *"perturbations"*) whose magnitude is significant to process experts. Besides, *PFs* are defined as *fuzzy-valued* continuous functions.

2.2.6 The constrained influences approach

This approach proposed by Bousson and Travé-Massuyès (1992a,b) is based on the combined use of causality and deep knowledge in terms of mathematical equations. This two level formalism has been devised so as to overcome the limitations of explicit causality 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 explicitly as a discrete set of linearly ordered time points, whose temporal spacing is as short as to capture the highest dynamics of the system. The causal model of a process is represented at a first level as both a causal network of interacting elementary dynamic systems, called qualitative automata or variables, influencing one another, and a second level as a set of constraints defining a restriction on the possible values of several variables.

At the first level, influences include the representation of activation conditions, time delay and response time. The second level is composed by functional constraints in the form of mathematical equations whose parameters take numeric interval values.

A cycle of the simulation algorithm includes three steps at every clock tick: run (1) perturbation propagation in the causal graph using an influence combination procedure (Bousson and Travé-Massuyès, 1993), (2) variable state updating, and (3) states filtering on the second level global constraints.

This section has provided an overview of the mathematical structures required to manipulate "symbolic numbers" and their properties as well as a brief presentation of different representation formalisms for physical systems. It is the authors' opinion that there is no point in comparing the formalisms in terms of advantages and limitations when disconnected from their context of use. Each of them was indeed devised for specific task and application domain requirements. The projects presented in the next section will make clearer each one's potential scope.

3 Application oriented work

In this part of the paper, we summarise approximately 40 projects with an application oriented flavour (and pointers to even more). We have organized this by dividing the application domains into six broad categories. These are: (see Table 1):

MAJOR APPLICATION AREAS
Continuous processes
Engineering
Ecology
Electronic circuits
Business and commerce
Medicine

Table 1 Major application areas

- *Continuous processes:* Work related to continuous, often dynamic systems, such as is common in process control, chemical engineering, power generations, etc. This work is further divided into the task of monitoring and diagnosis and the task of modelling and analysis.
- *Engineering:* Work related to the classical engineering fields or man-made physical systems, such as mechanical engineering or manufacturing. This work is further divided into the task of monitoring and diagnosis and the task of Design.
- *Ecology:* Work relating to natural ecological systems.
- *Electronic Circuits:* Work relating to diagnosis of electronic circuits including logical and analogical devices.
- *Business & commerce*: Work related to business management or financial trading.
- *Medicine*: Work related to explanation of diagnosis in medicine.

3.1 Continuous processes

Examples: *Monitoring and Diagnosis*
ARTIST: Chemical Plant and Electricity Network
DIAPASON: Illustrated With A Pulsed Column In A Nuclear Plant Distillation Column
CA-EN: Biotechnology Fermentation Process
Co-generation Plant
TIGER: Gas Turbines Condition Monitoring
SEXTANT: Nuclear Power Plants
QDIAG: Dynamic Systems Diagnosis
Waste Water Treatment

Table 2 Continuous processes

3.1.1 Monitoring and diagnosis

ARTIST: Chemical plant and electricity network

The ESPRIT Project ARTIST (Leitch *et al.*, 1991) 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. The ARTIST prototype implements a dependency recording model based approach. 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.*, at Heriot-Watt University in Scotland. They use 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, Siemens in Germany and CISE in Italy. The project ended in July 1993.

Bertin *et al.* describe work at CISE on monitoring and diagnosis of process control systems. The work in this paper was part of ESPRIT Project 820, a precursor to Artist. The authors were then part of the Artist project.

DIAPASON: Illustrated with a pulsed column in a Nuclear Plant

Another large European project is Diapason (Leyval and Gentin, 1991; Leyval and Ledoux, 1991; Montmain and Gentil; Rajagopolan, 1989). 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 presented in section 2.2 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 Montmain and Gentil (1991a,b). The system is still in prototype form but it includes a very sophisticated user interface.

Distillation column

The work by Feray-Beaumont (1991a,b) was in conjunction with the people working in Diapason. Hence the main focus and approaches are similar. The focus of the work is using qualitative reasoning for continuous process supervision. 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 at the University of Newcastle is now Dr F Corea.

CA-EN: Biotechnology Fermentation Process

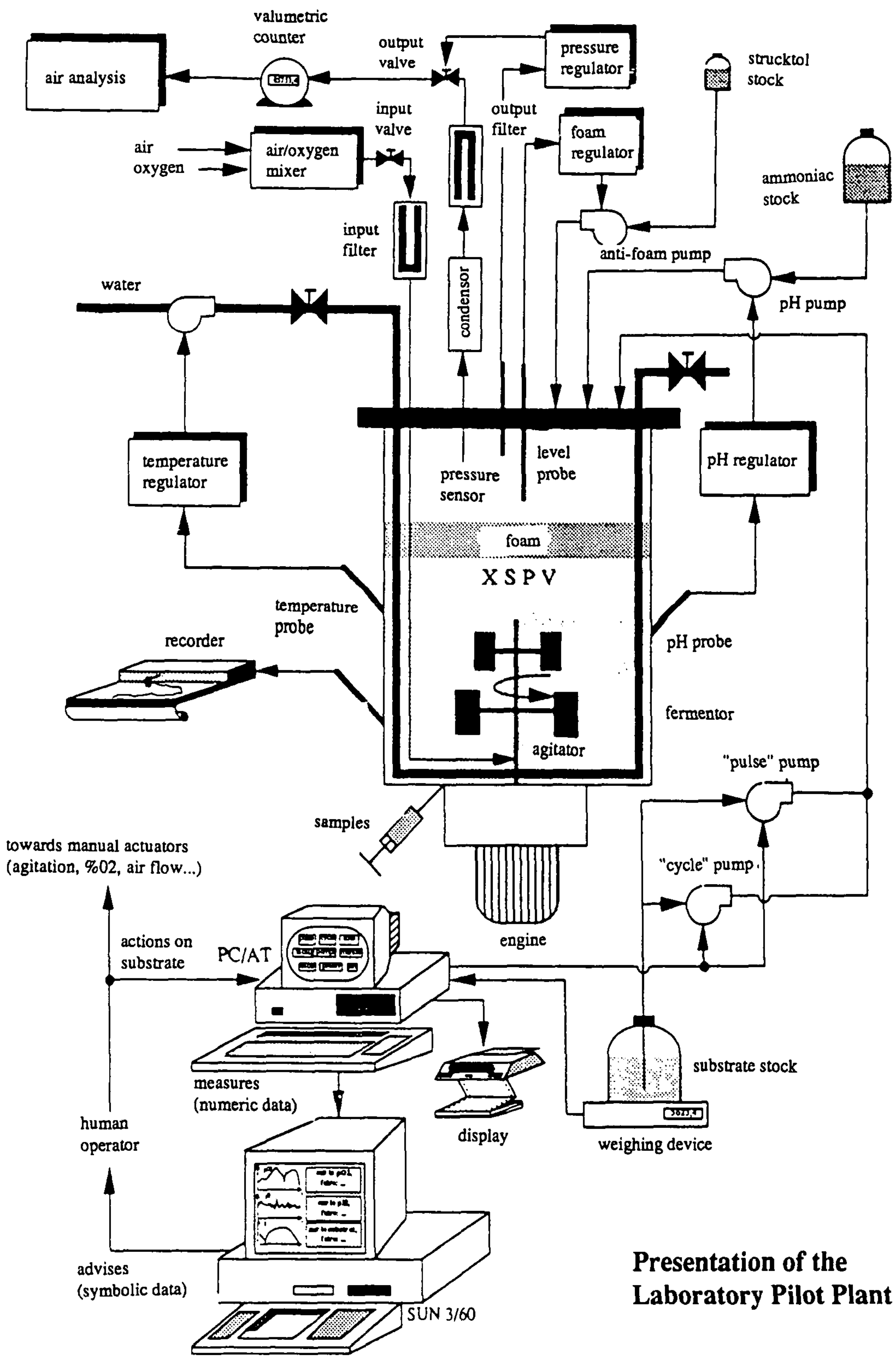
Travé-Massuyès *et al.* (Bousson *et al.*, 1993) are working on a process supervision system for a fed-batch biotechnology fermentation system. They are using the CA-EN tool which implements a Constrained Influences approach presented in section 2.2 in the prediction module (Bousson and Travé-Massuyès, 1992a, 1993). 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 behaviour; and (4) explaining the process behaviour by referring to its history.

Co-generation plant

Okuda, and Ushio (1991) 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.

TIGER: Gas Turbines Condition Monitoring

The ESPRIT project TIGER (Milne, 1992b, 1993) is a recent project that involves qualitative reasoning. This is lead by R Milne of Intelligent Applications (Milne, 1992a), and includes the



FROM: Bousson, Guerrin and Travé-Massuyès, 1993

Figure 2 Overview of the CA-EN biotechnology application environment; (b) Causal network of the fed-batch fermentation process. This is typical of the causal networks in many contemporary applications; (c) Fed-batch Fermentation Process. Example of the quality spaces and the predictions of the CA-EN qualitative simulator.

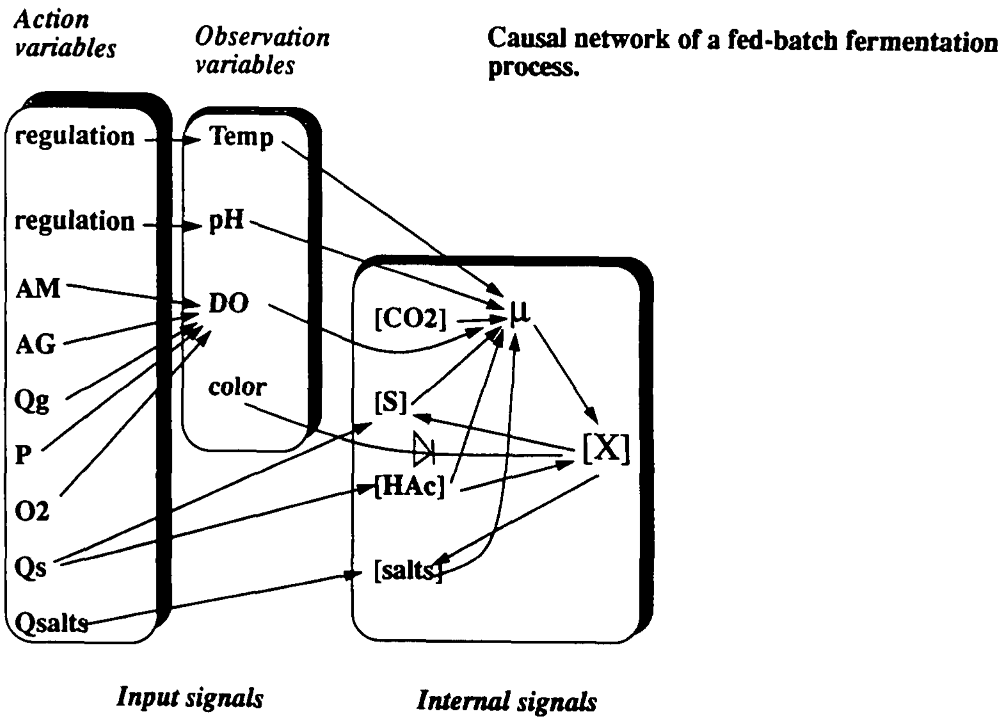
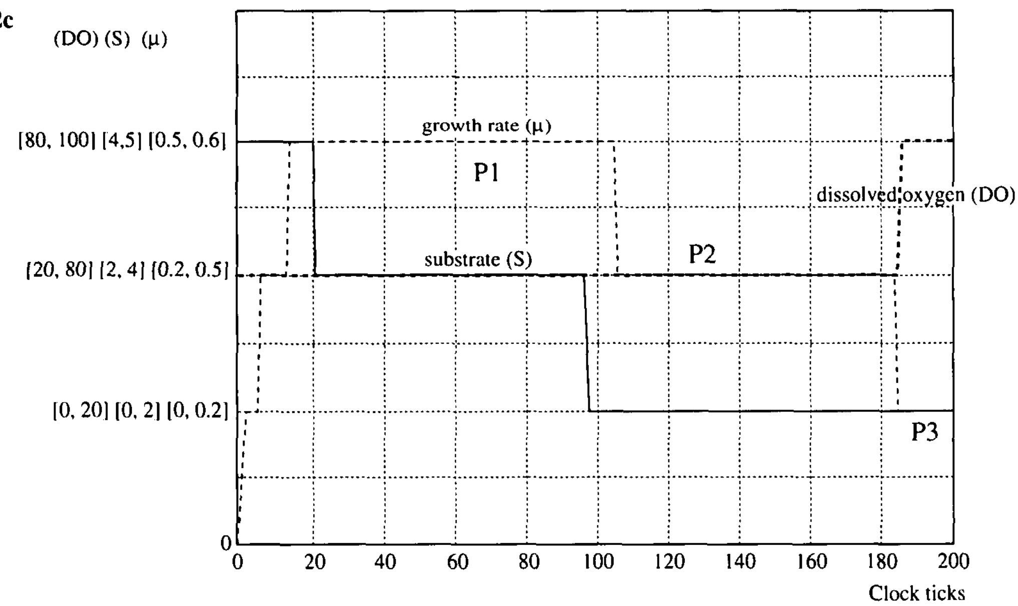


Fig 2b

Fig 2c



Simulation results of a fed-batch fermentation process

FED-BATCH FERMENTATION PROCESS

Quality spaces
DO (dissolved oxygen): {[0, 20[; [20, 80[; [80, 100]}
S (substrate): {[0, 2[; [2, 4[; [4, 5]}
μ (biomass specific growth rate): {[0, 0.2[; [0.2, 0.5[; [0.5, 0.6]}

Initial conditions
DO = 60%
S = 4.5 g/l
$\mu = 0$

Temporal unit = 3 seconds

Recognized patterns
P1: Main Metabolism Phase
$\mu > 0.5$
P2: Decline Phase
Decrease of μ after P1
P3: Substrate Limitation
$S < 0.05$

French QR groups of Travé-Massuyès of CNRS-LAAS and 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 being used is a recent version of the CA-EN predictor which includes more numeric reasoning than the one used in the biotechnology domain (refer to the project presented above). The CA-EN prediction module is used in a model-based diagnosis framework first, to provide the reference dynamic behaviour to which observed behaviour is compared, thus allowing discrepancy detection, and second, to perform candidate generation by searching backwards in the causal dependency graph of the models.

SEXTANT: Nuclear Power Plants

This project (Daniels and Feelders, 1990; Lucas and Evrard, 1993) has developed a diagnosis strategy based on a combined use of numeric and QSIM-like qualitative models. Qualitative models are used 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 (Charles, 1992) uses the qualitative simulator QSIM. It uses fault models which are simulated off line. The diagnosis module then follows the tree of behaviours corresponding to the observed evolution of the system, indicating the fault models which match the current system behaviour. The system has not been used in a real environment.

Waste Water Treatment

Tetreault *et al.* (1992) 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 numerical simulation. They are using QSIM, and only performing simulation so far.

3.1.2 Modelling and analysis

Examples: *Modelling and Analysis*
Cooling Circuit Of An Electrical Power Plant
Cold Trap In A Nuclear Power Plant

Table 3 Continuous processor

Cooling Circuit of an Electrical Power Plant

The work by Sugaya (1989) of ABB has as an application the cooling circuit for an electrical power generator. The focus is modelling and analysis. They use a device centred 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 (1991) 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. 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 was a study and the system is not in real use.

3.2 *Engineering*

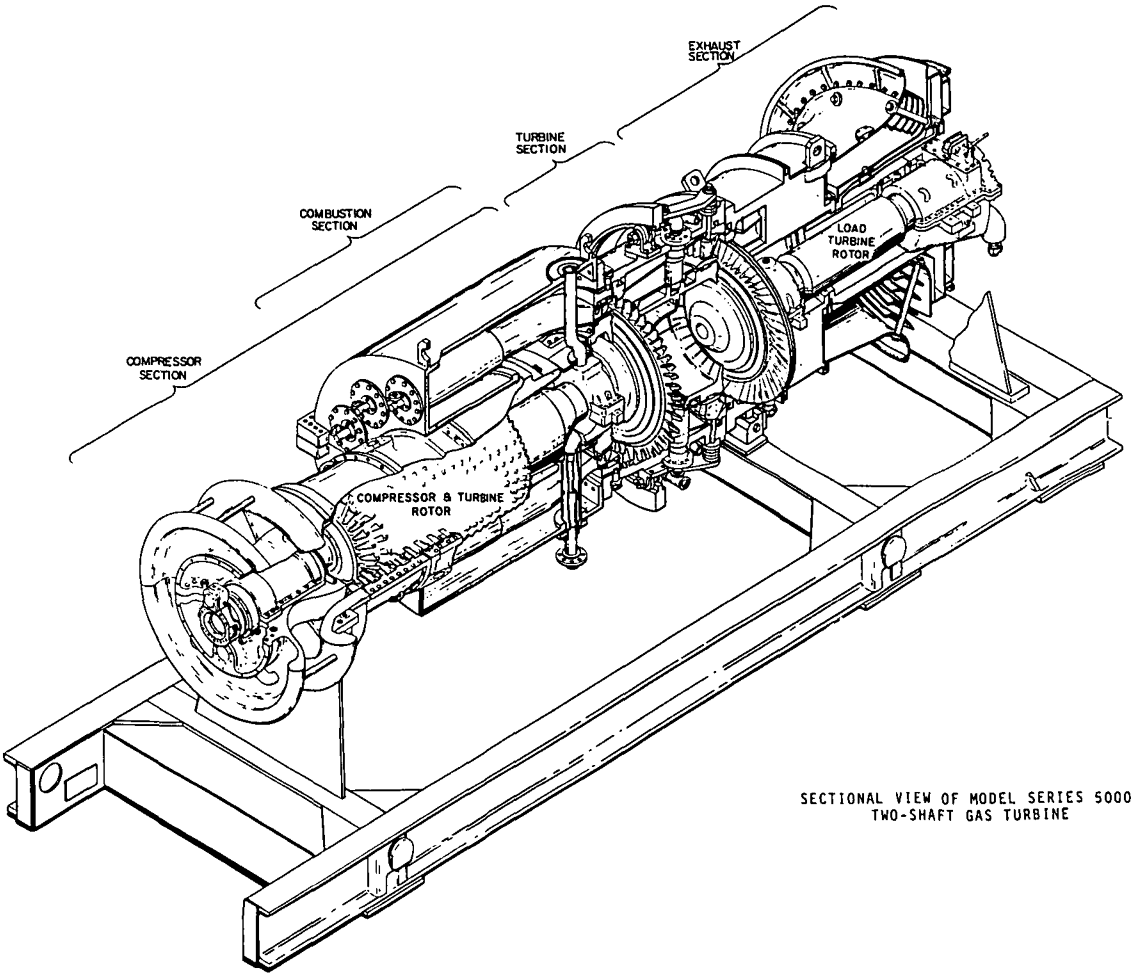
Examples: *Monitoring and Diagnosis*
CRACK: Steel Bridge Cracks
Hydraulic Circuits
Turbojet Engines
Vacuum For Semi-Conductor Fabrication
Automobile Screen Wash System
Naval Diesel Engine
CNC Machining Centres
Photocopier Machines
DIAMON: Monitoring and Diagnosis Of A Central Heating System
Central Heating System

Table 4 Engineering

3.2.1 *Monitoring and diagnosis*

Crack: Steel Bridge Cracks
CRACK stands for Consultant Reasoning About Cracking Knowledge (Roddis and Martin, 1991, 1992). 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 a consultant advisor to a bridge engineer to help him perform the needed analysis. The system has three levels: (1) a rule-based 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 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 done by Hogan *et al.* (1991) 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 based 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



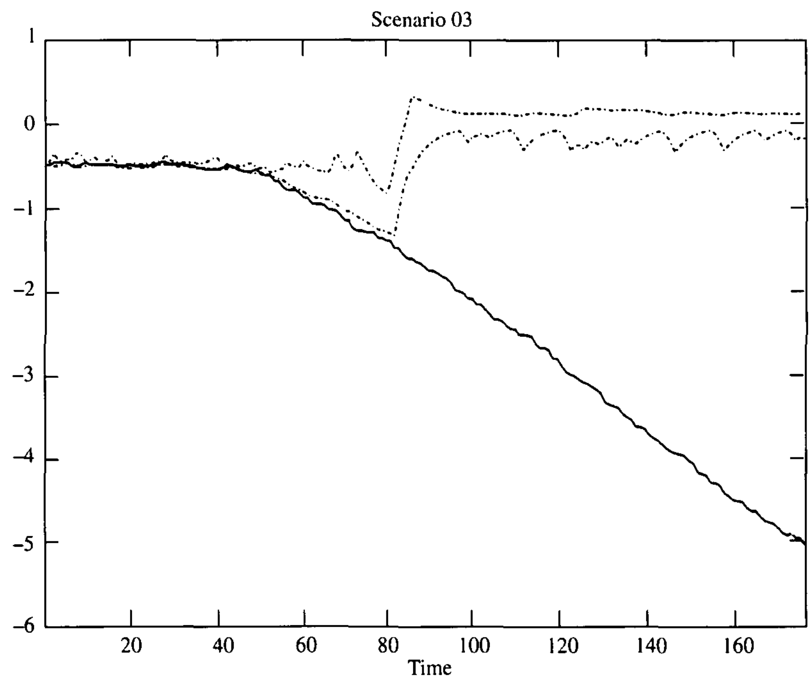


Figure 3 (a) Overview of the Tiger application Turbine; (b) CA-EN prediction of the 2nd stage nozzles servo control current, TANZ (in dotted lines), and the actual servo control current (solid line) when there is a fault with the 2nd Stage Nozzles servo system. Note that the fault is detected very early; (c) CA-EN prediction for the 2nd Stage Nozzles angle, TSNZ, (in dotted lines) and the actual nozzles angle (solid line). CA-EN correctly predicts the nozzle angle during a controlled, but oscillating decrease in turbine output

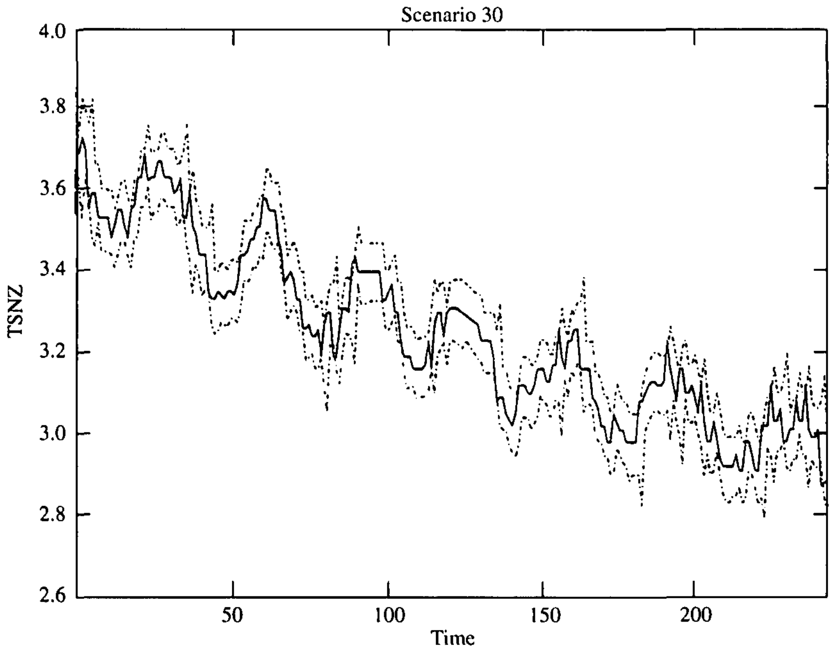


Figure 3c

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. The 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 only in the fluid power center.

Turbojet Engines

Rajagopalan (1984) 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 gives 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.* (1992), the main focus of this work is to bound weak qualitative models with dynamic envelopes in the QSIM system presented in section 2.2. 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. The application is just an example, although it is robust for the example given.

Automobile Screen Wash System

Hunt and Price (1989, 1991) and Price and Hunt (1989, 1991) 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 (1992) are working on an application for 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 and an example of how the system can detect the problem of a cooler becoming soiled. They also show how the qualitative model agrees with a numerical simulation.

CNC Machining Centres
Rehbold (1989) is working in the application area of diagnosis of CNC machining centres. 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 of these areas. They use their own style of model and propagate qualitative states. 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.* (1991) 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.

DIAMON: Monitoring and Diagnosis of a Central Heating System
Lackinger and Nejdl (1991) 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.

Central Heating System
Koch's (1992) 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.

3.2.2 Engineering design

Examples: *Engineering Design*
SQUALE: Air Supply For Space Suit
Electric Motors
Mechanical Systems
QDES: Mechanical Systems
Design On Automatic Process Discrete Control Systems

Table 5 Engineering

SQUALE: Air Supply for Space Suit
Zimmer and Travé-Massuyès work in the design of the air supply circuit for a space suit which was intended to be used with the Hermes space shuttle. They use their own tool, SQUALE (Missier *et al.*, 1993) which is a QDE-based qualitative simulator including formal calculus facilities.

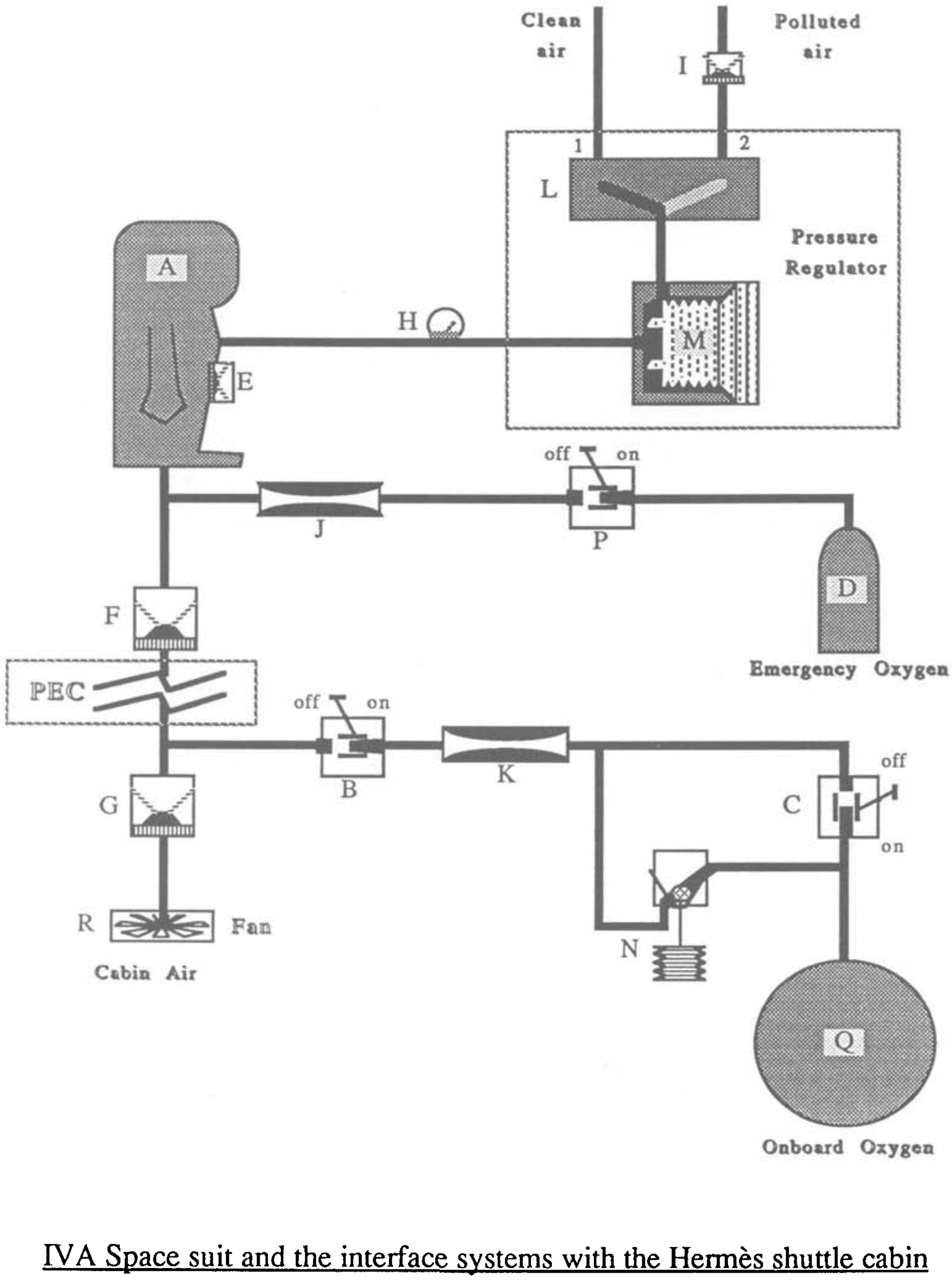


Figure 4 Schematic overview of the space suit design environment for SQUALE

SQUALE runs in connection with a representation language module specially designed for hydraulic circuits. SQUALE includes mechanisms for constraint handling and for reducing spurious behaviours. The goal is to use the qualitative situation to give all behaviours of the space suit system. These behaviours can then be evaluated to check for design problems or unwanted behaviours.

Electric Motors
Kiriyama, Tomiyama and Yoshikawa (1991a,b,c) 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 (1992) 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, generates fuller behavioural descriptions, and exploits kinematics more fully. They have demonstrated that the simulation algorithm captures the workings of most mechanical mechanisms by surveying 2500 mechanisms from an engineering encyclopedia. In their paper, they give examples of a feeder mechanism, brake shoe and a rim lock.

QDES: Mechanical Systems

Yannou (1993) proposes a design tool called QDES based on an envisionment like de Kleer and Brown's presented in section 2.2 and the representation of functional requirements related by design histories. The system detects the intersections between the expected behaviours (requirements) and the possible behaviours (envisionment) and helps the designer in the decision making process.

Design of Automatic Process Discrete Control Systems

Valisou (1992) in Finland focuses on the design of automatic process plant discrete control systems and on helping 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.

3.3 Ecology

Prediction in Plant Physiology
model of the cell cycle
intelligent tutor
QR for plants
qualitative model of the drop rate of apples
response of Ponderosa Pine trees to stress
model of an aquatic ecosystem
decision support system for crop management
animal habitat interaction

Table 6 Ecology

Prediction in Plant Physiology

The work by Rickel and Porter (1992) 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 rate?" 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 gives short descriptions of eight projects involving qualitative reasoning in the biological and ecological domains. Only a summary of the projects is included: (1) Gaglio models the cell cycle and the effects of anti-proliferate 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 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 (1991a,b); (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.

3.4 Electronic circuits

Diagnosis: OR Gate
Diagnosis: Analog Circuits

Table 7 Electronic circuits

Diagnosis: OR Gate
The application example in Mozetic (1991) 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 derives the qualitative model from the numerical one and he uses fault models to help with the diagnosis. He gives an example of an OR gate at the level of three npn transistors. This is an example to show his technique, not a real application.

Diagnosis: Analogue Circuits
Dague *et al.* (1987) are also working on troubleshooting of complex analogue circuits. The real focus is on diagnosis using relative order of magnitude reasoning (see the presentation in section 2.2). 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 is 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 sell a product called DIAGMASTER implementing this research.

3.5 Business and commerce

Diagnosis of Business Performance
Prediction: Market Exchanges
Prediction: Business Cash Flow

Table 8 Business and commerce

Diagnosis of Business Performance
Daniels and Feelders (1990a,b, 1991) are working on model based diagnosis of 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, and show how this can provide explanations for changes such as decrease in sales. Their approach is basically one of causal

and constraint static relations rather than simulation. They give an example that traces why a decrease in advertising, leads to a decrease in sales, which causes assets 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 (1991) 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. A prototype has been implemented.

Prediction: Business Cash Flow
Bailey *et al.* (1990) 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 *et al.* (1991a,b) give more detailed examples. The models and simulation are designed to help auditors. To diagnose problems, they use a fault model approach. The work is continuing but not in use yet.

3.6 Medicine

Explanation of Electrocardiograms
KARDIO: Interpretation of ECGs
Diagnosis: Cardiovascular System
Diagnosis: Thyroid Stimulating Immunoglobulin
Explanation: Metastatic Cancer Causes Brain Tumour

Table 9 Medicine

Explanation of Electrocardiograms
For Hunter *et al.* (1991a,b) 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 *et al.* (1989) 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 the company Telectronics in Australia.

Diagnosis: Cardiovascular System
Downing (1991) is working on qualitative model based diagnosis using the cardiovascular system. He combines a qualitative causal network with model based diagnosis techniques based on de

Kleer's 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 (1990) the application area is also medical 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 valves 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 Tumour
Parsons and Fox (1991) 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 tumour. They are using an extended version of Williams' Q1 approach. They also give an example of gastroenterological complaints such as ulcers and gall stones. The approach is shown to work on the two examples given.

3.7 Other areas

ELSA: Avalanche Path Analysis

Buisson (1991) developed a system called ELSA for avalanche path analysis. It is written in SHIRKA, an object oriented language. The system combines 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.* (1991) is 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 (Djerroud *et al.*, 1992) aims at building evolution scenarios for geoprospective analysis. They use a QTF approach as presented in section 2.2 and model the physical system in the line of Forbus' Qualitative Process Theory (see section 2.2 as well). A causal model allows them to propagate histories (piecewise linear temporal functions) by using the operators associated to every edge of the graph.

A Further Summary
The paper of Hunt Lee and Price 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 tools, rather than specific applications (for example, GDE and SHERLOCK).

4 Conclusion

This paper has given a summary of recent application oriented work. Although there are many 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 being developed, however, very few systems are in regular use. There is a trend towards more complex and ambitious projects. Whereas a few years ago, most of the work was paper based or laboratory examples, there is a gradual increase in the number of projects tackling real industrial applications and working with real application. A few years ago many projects had the aim of exploring an application area. But more recent projects, such as Tiger, have a clear goal of developing a system that will be used on a daily basis.

In spite of the small number of systems in daily usage, there are two products now available using QR techniques. The first is the Intelligent Pacemaker product based on the Kardio work. This is sold by Telectronics in Australia. The second is the Diagmaster product based on Dedale and sold by Electronique Serge Dassault. This is the best possible indication that QR techniques can be used for real applications.

One, perhaps surprising, observation is the range of application areas. The largest number of projects are in the traditional AI application areas of process control, engineering and medicine. But there are also a significant number of projects in areas where precise numerical modelling is difficult, such as business and ecology, and where the lack of physical laws of the domain is compensated for by a good understanding of the phenomena and internal mechanisms by the domain experts.

The three dominant tasks are:

- Monitoring and diagnosis
- Prediction and analysis
- Explanation.

Over 30% (14 out of 40) of the projects are using a qualitative modelling formalism based on qualitative differential equations. This is partly because QSIM was made available for free very early, and partly because in the first papers, the approach was well grounded on mathematical foundations stated with a systems theory flavour, which is familiar to the economics and engineering communities.

It is interesting to note that most people doing application-oriented work cite the need for the integration of qualitative and quantitative models. Despite the fact that quantitative models are available in many engineering domains, approaching the modelling problem at multiple levels of abstraction often leads to interesting and effective reasoning strategies. As a matter of fact, a general trend for the research is to build links with traditional numerical and analytical techniques.

A consensus is emerging of areas for further work and integration with other techniques that will be needed to make real, routinely useable, qualitative reasoning based applications. Multiple model based reasoning which was already mentioned above is one of these. This is related to model selection and model abstraction. Also because modelling is recognised as a complex task, the community is now putting significant effort into the automated modelling issue.

Finally, as a general statement, the community agrees that new formalisms and techniques must be guided by the tasks to be performed and that reasoning methodologies should be judged only with respect to the tasks they solve.

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