Qualitative Agents

For Assessing Human Reasoning in Process Supervision

Louise Travé-Massuyès
LAAS-CNRS & LEA-SICA
7, Avenue du Colonel Roche
31077 Toulouse Cedex
e-mail:louise@laas.fr

Francesc Prats, Mónica Sánchez
MA2-UPC & LEA-SICA
Pau Gargallo 5
08028 Barcelona
e-mail:{prats, monicas}@ma2.upc.es

Núria Agell
ESADE-URL & LEA-SICA
Av. Pedralbes, 62
08034 Barcelona
e-mail:agell@esade.es

Josette Pastor
INSERM U455
Service de Neurologie. CHU Purpan
31059 Toulouse Cedex
e-mail: josette@purpan.inserm.fr

Abstract

The WAHRPS (Worlds for Assessing Human Reasoning in Process Supervision) project aims at assessing the reasoning of patients suffering from a frontal syndrome. The methodology is based on comparing their performances to those of various Reference Artificial Reasoners (RAR), or Agents, when performing the supervision of a dynamic micro-world. Every RAR is considered to implement a specific cognitive style. This paper presents the concepts underlying the design of a qualitative agent as well as a method for comparing the behaviour of human operators in the corresponding cognitive style with the one proposed by the artificial agent.

Key words: Supervision Reasoning Assessment, Qualitative Reasoning, Micro-Worlds, Dynamic Systems.

1 Introduction

Understanding and assessing human reasoning about dynamic situations is a highly complex task, which is central to several scientific areas such as neuropsychology, human factors' research and artificial intelligence. A typical case is the supervision of dynamic systems, for instance in industrial production plant environments or in the air traffic control domain (Cellier 1996). Several accidents occurred during the last decade have pointed out the increasing need for better understanding the different cognitive components of human supervision reasoning – anticipation, diagnosis, decision making, etc. – as well as the human-machine interface impact.

This has a link with the medical domain as it has been noticed that some human errors arising from information overload, stress or fatigue in the process supervision domain (Woods *et al.* 1987) can also be observed on patients suffering from Parkinson Disease (Brown 1991). As a matter of fact, some patients with a Parkinson disease present a "frontal-type syndrome", which is suspected of impairing many cognitive components involved in their reasoning about dynamic situations.

Whereas direct observation of the operators at work is one of the most commonly used method in the human factors and knowledge engineering communities, it is admitted that experimental environments based on simulators or micro-worlds (Hoc 1994) offer significant advantages such as the reproducibility of the experiments.

The WAHRPS (*Worlds for Assessing Human Reasoning in Process Supervision*) project, conducted by INSERM U455, aims at providing an experimental environment and a methodology for the assessment of reasoning in process supervision. The methodology is based on comparing the subjects' performances to those of various *Reference Artificial Reasoners* (RAR), or Agents, when performing the supervision of a dynamic micro-world (Pastor et al. 1998). Every RAR is considered to implement a specific cognitive style. A user-friendly and powerful micro-world shell has been specifically designed for this purpose (Pasquet 1995a).

The aim of this paper is to present the concepts underlying the design of a naïve qualitative agent (Travé-Massuyès 1997) as well as a method for comparing the behaviour (i.e. the sequence of actions) of the subjects that undergo the test with the one implemented in the artificial agent.

2 The micro-world shell

The Wahrps environment includes a generator of micro-worlds that allows one to define and build dynamic micro-worlds and software that simulates their behaviour (Pasquet 1995a). The micro-worlds are in the form of waterworks, which may undertake all the characteristics of complex dynamic systems, such as decomposability and non-linearity.

A WAHRPS micro-world is composed of a set of *tanks*, linked by a set of *pipes*, each of which may or may not include a *binary action valve*. The idea of the micro-worlds' was inspired from the more complex, "industry-like", structures (pumps ...) designed by Morris *et al.* (1985) A similar micro-world was used in (Morris *et al.*

1985) although it also included pumps. In Wahrps, only components that do not require technical skills have been selected so that the micro-world is independent of the subject's cultural background.

The micro-world shell fulfils several important requirements:

- The micro-world physics domain (hydraulics) is sufficiently grounded in everyday life concepts (gravity flowing water) so as to allow one to test patients;
- It is of sufficient "industrial realism" so as to be accepted by industrial operators;
- It allows one to build highly flexible micro-world structures, which may easily vary in the type of situation and their complexity. .

2.1 Case Study: the Micro-World Configuration

A micro-world is defined by the following parameters:

- Number of tanks: n.
- For each tank T_i, $i=1,...,n$, C_i represents its capacity, H_i its height, and W_i its width. All the tanks are assumed to have the same deepness, $D_i = D$, $i = 1,...,n$, so that the micro-world is projected in a bidimensional space consistent with the perception provided by a planar graphical interface.
- For each pipe P_{ij}, T_i is the upstream tank, T_j the downstream tank, H_{ij} the height, L_{ij} the "diagonal" length (i.e. the distance between the bottom of T_i and the top of T_j), W_{ij} the mean width and β_{ij} a constant that depends on the pipe P_{ij} and on the gravitation constant g. If a valve controls the pipe P_{ij} flow, the valve is denoted by V_{ij}.

  By assumption, a pair of tanks T_i and T_j cannot be connected by more than one pipe.

Two tanks are differentiated from the other ones: the *source tank*, always referred to as T_1, which is at the very top of the configuration and the *sink tank*, always referred to as T_n, which is at the very bottom. Both tanks' capacities are set to be the same. The other tanks are referred to as the *intermediary level tanks*.

At the beginning of a session all the tanks are empty but the source tank T_1. The instruction given to the operator, called *THE INSTRUCTION* in the following, is that *he/she must convey water from the source tank T_1 to the sink tank T_n, avoiding the intermediary tanks to overflow, and in minimum time, by acting on the binary valves controlling the pipes.* The operator knows that water propagates through the pipes under the effect of gravity, the propagation being only constrained by the closing of the ON/OFF valves.

The set of *top tanks*, which evolves according to the dynamics of the system, is defined as the set of non empty tanks whose upstream tanks are all empty.

A micro-world configuration instance at a given time of a test session is given in figure 1. It will be referred to this particular micro-world configuration all along the paper to illustrate the proposed concepts, explanations and ideas.

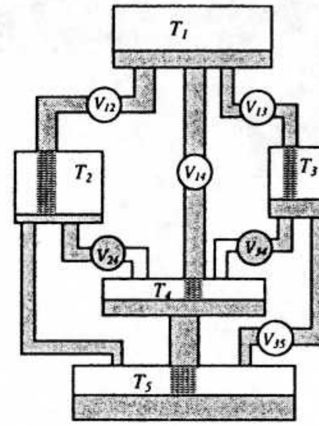

Figure 1: A micro-world configuration

2.2 Formal Representation of the Physical System

The physical tank configuration system and the flowing processes occurring in it can be formally represented by an oriented graph $G = (V,A)$. The set of vertices $V=\{T_1,...,T_n\}$ corresponds to the tanks and the set of arcs $A=\{(T_i, T_j)| T_i, T_j \in V$ and there exists a pipe P_{ij} from T_i to $T_j\}$ corresponds to the set of pipes P_{ij}. For sake of clarity, the arc (T_i, T_j) is hence denoted by P_{ij}. The arcs of G are oriented in such a way that the source tank T_1 and the sink tank T_n are the source and the sink of the graph respectively.

Weights 0 or 1 are associated to each arc of G, depending on whether the corresponding valve is closed or open, respectively. If a pipe includes no valve, its weight is always 1. The arcs with weight 1 (weight 0) are graphically represented by continuous lines (discontinuous lines) (cf. figure 2).

The state of the system is assessed within a linear temporal scale provided by a logical clock. The arcs weight values evolve in time as the operator acts on the valves.

A *path* in G is defined as a sequence $(P_{i1i2}, P_{i2i3},...,P_{i(k-1)ik})$ of arcs. It starts from tank T_{i1} and ends at tank T_{ik}.

At some time point, an *open path* in G is defined as a path such that all arcs have weight 1.

Figure 2 represents the oriented graph corresponding to the system in figure 1.

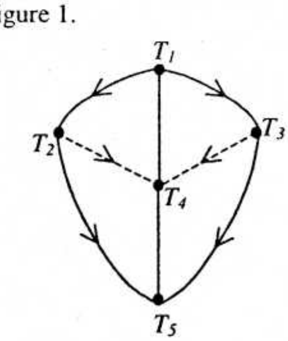

Figure 2: The oriented graph

3 Naïve Qualitative Agent (NQA)

Three specific agents, based on anticipating the process behaviour by means of a simulation and on choosing the best action according to a three steps ahead prediction strategy, have already been built (Pasquet 1995b) (Pastor et al. 1998). The first one, referred as the numeric agent, uses a numerical fluid mechanics model. The other two were implemented using the causal simulator Ca-En (Bousson 1994). These two later ones differ in that the first is based on a semi-qualitative version of the fluid mechanics model whereas the second relies on common sense qualitative laws. The action choice strategy underlying the three agents was shown to be similar to that used by some humans (Pastor et al. 1998).

On the short-term, prediction of the system's future states by human subjects has been observed to be as precise as the numeric agent and certainly much better than the (semi)-qualitative simulation based agents (Pastor et al. 1998). This does not mean that humans really compute numerically the states. More probably, their performance is due to a kind of "perceptual prediction": the water heights in the tanks being continuously displayed, humans may anticipate the immediate future heights. Qualitative simulation of the states cannot therefore compete with humans at this level. However, it is known that human brain shows an extraordinary ability to categorise in order to perform the most rapid and efficient reasoning. We assume therefore that they draw from the predicted precise states the qualitative information that is adequate for the problem, i.e. "levels of danger" (alarms). This paper proposes an artificial agent built along theses lines: starting from a numeric perception, it abstracts this information into qualitative concepts that are processed with qualitative reasoning techniques (Travé-Massuyès 1997). The primary perceptions that a human being undergoes when facing up a WAHRPS micro-world are supposed to be the heights of water in the tanks and their tendencies, i.e. whether they are increasing, decreasing or steady. Our assumption is that these are the main factors that a human being takes into account for deciding about an action to perform. Which action to perform may be decided upon a qualitative representation of the world, generally supported by a causal representation (Kirwan 1992). On the other hand, psychologists commonly agree on the fact that anticipation is a crucial aspect in process supervision reasoning (Cellier 1991). The operators are hence suspected to use the causal mental model to perform predictions that are qualitative in nature. These are the features that characterise the Naïve Qualitative Agent (NQA) with respect to other agents in the artificial operators library.

It is important to understand that the agents' design is not driven by efficiency goals but rather by cognitive plausibility.

3.1 The agent perception model

According to the precedent considerations, a qualitative representation of the height of water in the tanks and the tendency of these heights is introduced by means of two qualitative variables associated to each tank T_i, $i=1,...,n$, at each instant t:

1. The height of water $h_i(t)$ may take four possible qualitative values:

- $h_i(t)$ is EMPTY (0) when $h_i(t) = 0$.
- $h_i(t)$ is LOW if it is below a given threshold α_i, which specifies a criticality level and is used to trigger an alarm. This alarm is an anticipatory indicator in the control strategy (cf. Section 3.2).
- $h_i(t)$ is HIGH when $\alpha_i \leq h_i(t) < H_i$.
- $h_i(t)$ is FULL when $h_i(t)=H_i$.

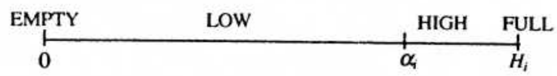

Figure 3: Qualitative values of the height of water

Threshold setting: The alarm threshold α_i is determined such that the volume of water admissible in tank T_i before it overflows, i.e. C_i-$h_i(t)W_iD$, equals a given constant K, the same for all tanks. The value of the landmark α_i is hence given by C_i-$\alpha_i W_i D$= $H_i W_i D$-$\alpha_i W_i D$ = K, therefore $\alpha_i = H_i - K/(W_iD)$.

This way of setting the alarm threshold guarantees that the alarms correspond to the same level of criticality for all tanks. It is based on the assumption that humans make use of a natural perception of the width of the tanks and understand the relation between height, width, deepness and volume (which in our bidimensional case comes back to the relation between height, width and surface). More naïve cognitive options are not excluded, for instance the threshold α_i could be set on the height of the tank, i.e., $\alpha_i=kH_i$, rather than on the volume. This must be considered as one of the options that should allow us to "tune" the agent according to a given category of human beings.

2. The tendency of the water height in the tank, $\partial h_i(t)$, may take three possible qualitative values: inc, dec and std (meaning "increasing", "decreasing" and "steady" respectively):

- If $h_i(t) - h_i(t-1) > 0$, then $\partial h_i(t) = inc$.
- If $h_i(t) - h_i(t-1) < 0$, then $\partial h_i(t) = dec$.
- If $h_i(t) - h_i(t-1)= 0$, then $\partial h_i(t) = std$.

At each instant t, each valve has an associated value 1 or 0, depending on whether it is open or closed, respectively.

3.2 Control strategy

At each instant t, a tank T_i is said to be *alarming (Al)* if its height of water $h_i(t)$ is HIGH or FULL, and its tendency $\partial h_i(t) = inc$.

Intuition advises one to distinguish two cases: the case with alarms in which there is one or several tanks overflowing or about to overflow (i.e. there are alarming tanks) and the case without alarms (i.e. no alarming tanks). In each of these two cases, the goals are different, and so are the corresponding strategies that the NQA carries out.

3.2.1 Case without alarms

3.2.1.1 Goals

When there are no alarms, the main objective is to accelerate the process, i.e., to transport the maximum quantity of water from the top tanks to tank T_n at each instant. This objective is a direct answer to the minimum time requirement of THE INSTRUCTION and can be interpreted in practical terms by the following goals:

1. *Achieve and maintain an increasing tendency for the sink tank T_n, i.e. $\partial h_n(t) = inc.$*
2. *Increase at the most the number of open paths from the top tanks to the sink tank T_n.*

The first instruction aims at avoiding the situation in which there are no open paths. The second instruction expresses the acceleration goal.

The action to be performed is hence chosen according to the number of supplementary paths that it opens. If two actions have the same consequence to this respect, a criterion based on the maximal flow allowed by the new open paths is applied. This is described in more details in the next section.

3.2.1.2 Method

Taking into account the goals above, the *admissible* actions are defined as those that do not close any valve. The method uses the graph G and the weights associated to its arcs.

At each instant t with no alarm, do:

Step 1: Compute the paths starting from a top tank and ending at tank T_n:

- If $t = 0$, compute the set of all possible paths starting from the source tank T_1 and ending at the sink tank T_n. This set is called $\mathcal{P}_0$.
- If $t = k \neq 0$, update the paths in the set $\mathcal{P}_{k-1}$ as follows: the path $(P_{i1i2}, P_{i2i3}, \ldots, P_{(il)n}) \in \mathcal{P}_{k-1}$ is updated by removing the head sub-path $(P_{i1i2}, \ldots, P_{i(z-1)iz})$, $z \leq l$, corresponding to EMPTY tanks.

/As T_1 and the following tanks of the oriented graph are getting EMPTY, the paths must be updated so as to start at the first not empty tank, i.e. a top tank/

Step 2: Label the paths in $\mathcal{P}_t$ with the number of arcs having a weight equal to 0.

/This number corresponds to the number of actions to be performed for opening the path/

Step 3: Determine the action to be performed.

1. If all the paths are open, the action of the NQA is to do nothing.
2. Otherwise, consider the paths with a minimum label.

When there is only one path, the action of the NQA is to open the closed valve of this path which is the closest to T_n[1].

When there are more than one path, the NQA uses the "min-max criterion" given below in order to select one of them.

Min-max criterion: Given the set of paths p_i, $i=1,\ldots,k$ with minimum label, compute for each p_i the minimum width of its pipes (min-width)$_i$; select the path that has the maximum (min-width) value.

If the Min-max criterion provides a path, the action of the NQA is to open the closed valve of this path that is the closest to T_n.

If the Min-max criterion provides several paths, the choice of one of these paths is made randomly.

3.2.2 Case with alarms

3.2.2.1 Goals

When one or several alarms are active, the main objective is to come back to a non-alarming situation; nevertheless, the general objective of accelerating the process is maintained. Therefore the goals are the following, ordered by importance:

1. Do not enlarge any alarm.
2. Reduce the number of alarms.
3. Achieve and maintain the tank T_n increasing.
4. Increase at the most the number of open paths to tank T_n.

The first instruction means that when a tank is alarming, the operator is required not to open (close) any valve on an upstream (downstream) pipe. The second expresses the goal of coming back to a non-alarming situation. The third and fourth are the same as for the case without alarms, as the acceleration goal still holds.

3.2.2.2 Method

The given method is based on a qualitative one-step ahead prediction after the computation of all the possible actions that may remove alarms, denoted as admissible actions.

At each instant t with alarms, do:

Step 1: Compute the set $\mathcal{A}$ of admissible actions:

For each alarm Al_i (alarming tank T_i) compute all the possible actions that may remove Al_i. These actions are:

1) Direct actions:

- to close the nearest valve of an open path arriving at tank T_i[2],
- to open the valve of a pipe going out directly from tank T_i,

If no direct action is applicable:

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[1] An alternative strategy would be to open the closed valve closest to the top tank of the path. This option is more risky, in the sense that it may result in alarming situations more often.

[2] It could also be considered to close a valve more distant from the alarming tank, but the inertia of the system makes this type of action much less intuitive than the proposed one.

2) Indirect actions

- to open a valve on a pipe going out from one of the nearest tanks upstream T_i.

If no indirect action is applicable

3) No action

Step 2: Perform a qualitative one-step ahead prediction:

For each admissible action, a one-step ahead qualitative prediction is performed on the basis of the graph G that can be viewed as a representation of the causal influences underlying the flow processes.

An action on a valve V_{ij} influences a subset of tanks whose vertices define a sub-graph of G, say $G_{V_{ij}}$. The vertices of this sub-graph are:

- T_i and its downstream tanks on the open paths that do not include V_{ij}, denoted as $G_{V_{ij}}(T_i)$.
- T_j and its downstream tanks on the open paths, denoted as $G_{V_{ij}}(T_j)$.

T_i and T_j undergo *direct influences* whereas the other tanks only undergo *indirect influences*. Note that $G_{V_{ij}}(T_i)$ may intersect $G_{V_{ij}}(T_j)$ and that T_j may belong to $G_{V_{ij}}(T_i)$. The overlapping tanks undergo several influences.

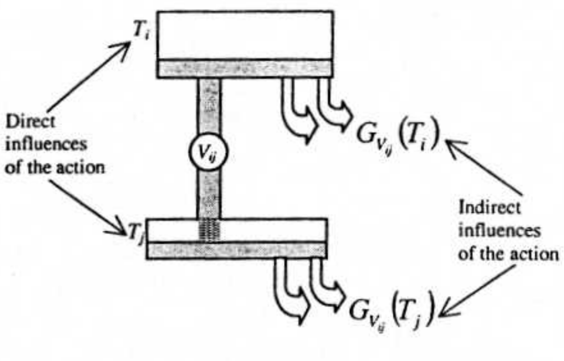

Figure 4: Direct and indirect influences

Then, for every tank in $G_{V_{ij}}$, the prediction consists in:

1. Computing and combining the *marginal influences* (direct and indirect) undergone by the tank, i.e. the effects of the action through different paths. Positive (negative) influences indicate that the speed of the tank volume evolution (volume derivative) is increased (decreased). Positive and negative direct influences are labelled with $+\infty$ and $-\infty$, respectively. Positive and negative indirect influences are labelled with $+1$ and -1, respectively (cf. table 1).

	T_i	$\forall T_k \in G_V(T_i)$	T_j	$\forall T_l \in G_V(T_j)$
Opening V_{ij}	$-\infty$	-1	$+\infty$	$+1$
Closing V_{ij}	$+\infty$	$+1$	$-\infty$	-1

table 1: influences resulting from an action on valve V_{ij}

The various influences undergone by the tank are combined into a qualitative descriptor Σ given by the sign of the sum of the marginal influences, assuming that the sum is operated on the extended real line $\mathbb{R} \cup \{+\infty, -\infty\}$. If the sum is zero, then no descriptor is assigned.

2. Adding the qualitative descriptor (+ or −) determined from Σ (cf. table 2)

- to the label of tendency (*inc* or *dec*) of the tanks, or, if the tendency is *std*, changing the std label into *inc* or *dec*.
- to the label *Al* of the alarming tanks.

Σ=+	Σ=−
$inc \rightarrow inc^+$	$inc \rightarrow inc^-$
$dec \rightarrow dec^-$	$dec \rightarrow dec^+$
$std \rightarrow inc$	$std \rightarrow dec$
$Al \rightarrow Al^+$	$Al \rightarrow Al^-$

table 2: Addition of a qualitative descriptor

The extended labels correspond to the following intuitive idea, given through an example: if a valve that is upstream an increasing tank is opened, this tank increases even more, hence the new label *inc*$^+$; if it is closed, the height of water in the tank increases less, hence the new label *inc*$^-$ [3].

Step 3: Choose the action to be performed:

Admissible actions are evaluated according to the goals on the basis of the predictions of step 2.

Four grades G_1, G_2, G_3 and G_4, corresponding to the goals 1, 2, 3 and 4 given in 3.2.2.1 are assigned to every admissible action. Positive grades represent an improvement, and negative ones represent a deterioration of the situation.

1. If the action generates n alarms Al^+, $n \geq 0$, then $G_1 = -n$.
2. If the number of alarms that have been labelled with Al^- is n, and the number of new alarms Al is m, then $G_2 = n - m$.
3. If the state of tank T_n is *inc*$^+$, then $G_3=2$. If the state of tank T_n is *inc* or *inc*$^-$, then $G_3=1$. If the state of tank T_n is *std*, then $G_3=0$.
4. If the number of open paths to the sink tank has been increased by n, then $G_4=n$. If it has been decreased by n, then $G_4=-n$. If it has remained constant, then $G_4=0$.

After this grading, the way of choosing the action relies on the computation of a global grade Assign weights p_1, p_2, p_3, p_4, such that $p_1 > p_2 > p_3 > p_4 > 0$ and normalised such that $p_1 + p_2 + p_3 + p_4 = 1$, respectively to each goal and compute the global grade G as the weighted sum $G = p_1{*}G_1 + p_2{*}G_2 + p_3{*}G_3 + p_4{*}G_4$, for every action. The NQA chooses the action that obtains the greatest grade G. In case of ambiguity, the NQA chooses randomly any of the actions with maximal grade G.

[3] inc$^-$ could be std as well, but the qualitative nature of the prediction does not allow us to distinguish the two cases.

Example 3.1

This example shows the one-step prediction process (Step 2) and the action choice (Step 3), for a particular case with two alarming tanks. Let's consider the micro-world given in figure 1 and assume that at instant t tanks T_3 and T_4 are alarming, as represented by the graph in figure 5.

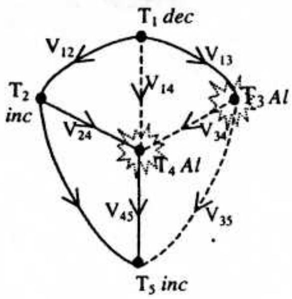

Figure 5: Example with two alarming tanks

The admissible actions that may remove Al_3 are: to close valve V_{13}, to open V_{34} or to open V_{35}, and the only admissible action for removing Al_4 is to close valve V_{24}.

Then, for each one of these four admissible actions, the one-step qualitative prediction is performed in the following way:

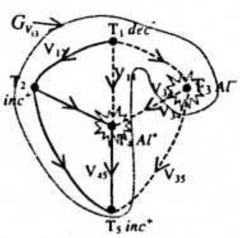

Figure 6: Closing V_{13}

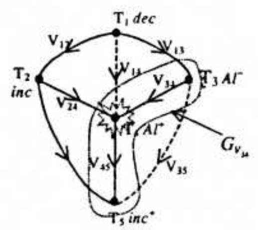

Figure 7: Opening V_{34}

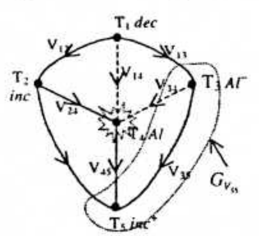

Figure 8: Opening V_{35}

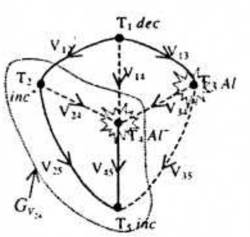

Figure 9: Closing V_{24}

The four grades G_1, G_2, G_3 and G_4 assigned to every admissible action are the following:

- Closing V_{13}: $G_1 = -1$, $G_2 = 1$, $G_3 = 2$, $G_4 = 0$.
- Opening V_{34}: $G_1 = -1$, $G_2 = 1$, $G_3 = 2$, $G_4 = 1$.
- Opening V_{35}: $G_1 = 0$, $G_2 = 1$, $G_3 = 2$, $G_4 = 1$.
- Closing V_{24}: $G_1 = 0$, $G_2 = 1$, $G_3 = 1$, $G_4 = -1$.

Given the weights $p_1 = 0.4$, $p_2 = 0.3$, $p_3 = 0.2$, and $p_4 = 0.1$, every action is characterised by its global grade.: Closing $V_{13} \leftrightarrow G=0.3$, Opening $V_{34} \leftrightarrow G= 0.4$, Opening $V_{35} \leftrightarrow G=0.8$, and Closing $V_{24} \leftrightarrow G=0.4$. Hence the NQA chooses the action that obtains the greatest grade, i.e. Opening V_{35}.

4 Refining the agent perception and reasoning (QA)

A more refined way, though still qualitative, for the computation of the "tendencies of the water height" of each tank is presented in this section. The resulting qualitative agent (QA) is able to quantify the tendencies and to account for alarm levels, depending on the relation between the widths of the open pipes arriving to a tank and those going out.

The advantage of the QA with respect to the former NQA is that it is more accurate without requiring much more computational effort. The kind of quantification based on pipes width is an aspect of the reasoning that may be involved in more elaborated human decision making strategies.

4.1 The refined perception model

As in the NQA, at each instant t, two qualitative variables are considered for each tank T_i:

1. The height of water $h_i(t)$ which is the same as for the NQA. Let's recall that it may take four qualitative values: EMPTY (0), LOW, HIGH, and FULL (equal to the total height H_i).
2. The tendency of the water height: $\partial h_i(t)$, which may now take five qualitative values: *incL*, *incS*, *decL*, *decS* and *std* (meaning "increasing a lot", "increasing slightly", "decreasing a lot", "decreasing slightly", and "steady", respectively). The labels are obtained as explained below:

   Let $W_{a_1i}, W_{a_2i}, ..., W_{a_ki}$ be the widths of the open pipes arriving to tank T_i and $W_{io_1}, W_{io_2}, ..., W_{io_z}$ the widths of the open pipes going out from it at instant t, and consider the quotient

   $$Q_i(t) = (W_{a_1i} + W_{a_2i} + ... + W_{a_ki}) / (W_{io_1} + W_{io_2} + ... + W_{io_z}).$$

   The possible values of this quotient determine the five possible qualitative values of the tendency $\partial h_i(t)$, as given in the following table:

$Q_i(t) > 1$	$Q_i(t) \geq 3 \rightarrow \partial h_i(t) = incL$
	$1 < Q_i(t) < 3 \rightarrow \partial h_i(t) = incS$
$Q_i(t) < 1$	$Q_i(t) \leq 1/3 \rightarrow \partial h_i(t) = decL$
	$1/3 < Q_i(t) < 1 \rightarrow \partial h_i(t) = decS$
$Q_i(t) = 1$	$\rightarrow \partial h_i(t) = std$

table 3: Qualitative values of $\partial h_i(t)$

If $Q_i(t) > 1$, there is more water going into the tank than going out from the tank, so the height of water in the tank is increasing. We assume that a human being is able to differentiate the situation when the input and output pipes total widths are in a proportion above 3. Therefore, 3 is taken as a threshold for the two different levels of increasing, *incL* and *incS*.

If $Q_i(t) < 1$, the height of water in the tank is decreasing. Following a similar reasoning as before, two different levels for decreasing, *decL* and *decS*, are considered for a threshold at 1/3.

If $Q_i(t) = 1$, the assigned label is *std*.

4.2 The refined control strategy

As the NQA, the QA distinguishes two cases: with or without alarms.

At each instant *t*, a tank T_i is said to be *alarming* when its height of water $h_i(t)$ is HIGH or FULL, and its tendency $\partial h_i(t)$ is either *incL* or *incS*. The first corresponds to a *large alarm* and the later case to a *small alarm*.

When there are no alarms, both operators NQA and QA have the same strategy for deciding at each instant which action to perform. The reasoning is different in the case with alarms.

4.2.1 Case with alarms

4.2.1.1 Goals

The goals of the QA are the following, ordered by importance:

1. *Do not generate large alarms.*
2. *Reduce the number of alarms.*
3. *Maintain the tank T_n increasing.*
4. *Increase at the most the number of open paths to tank T_n.*

These are the same as for the NQA, except for the first one, which is now formulated by means of the levels of alarms.

4.2.1.2 Method

The method remains similar to the one for the NQA in its principles and it includes the same steps.

At each instant *t* with alarms, do:

Step 1: Compute the set of admissible actions (identical to the NQA)

Step 2: Perform a qualitative one-step ahead prediction

For each admissible action, a one-step ahead qualitative prediction is performed on the basis of the graph *G*. Let's recall that

$$G_{V_{ij}} = G_{V_{ij}}(T_i) \cup G_{V_{ij}}(T_j) \cup \{T_i, T_j\},$$

and is defined as for the NQA in 3.2.2.2.

The prediction procedure is different for T_i and T_j, for which the quotient $Q_i(t)$ changes, and for the other tanks in $G_{V_{ij}}$. It consists in:

1) Computing for T_i and T_j the new quotients $Q_i(t+1)$ and $Q_j(t+1)$ that would result at the instant $t+1$ from doing the action and assign the new tendency and alarm labels as indicated in Table 3.

2) Computing and combining the *marginal influences* (all come from *indirect* influences) undergone by the tanks in $G_{V_{ij}} - \{T_i, T_j\}$. This is performed in a similar way as for the NQA, i.e., positive and negative indirect influences are labelled +1 and −1, respectively. Then add a qualitative descriptor Σ given by the sign of the sum of the marginal influences to the tendency and alarm labels in the following way (only the cases used in step 3 for choosing the action are listed):

Σ=+	Σ=−
$incS \rightarrow incS^+$	$incS \rightarrow incS^-$
$AlS \rightarrow AlS^+$	$AlS \rightarrow AlS^-$
$incL \rightarrow incL^+$	$incL \rightarrow incL^-$
$AlL \rightarrow AlL^+$	$AlL \rightarrow AlL^-$

table 4:The qualitative descriptor Σ

Step 3: Choose the action to be performed

Four grades G_1, G_2, G_3 and G_4, corresponding to the goals 1, 2, 3 and 4 given in 4.2.1.1 are assigned to every admissible action:

1. If the action generates n_1 new *AlL* and n_1' AlL^+, then $G_1 = -(n_1 + n_1')$
2. Determine:
   - the number of *AlS* and *AlL* that have been eliminated: n_2, n_3, respectively ;
   - the number of AlS^- and AlL^-: n_4, n_5, respectively;
   - the number of new *AlS* and *AlL*: n_6, n_7, respectively;
   - the number of AlS^+ and AlL^+: n_8, n_9, respectively.

   Then $G_2 = n_2 + n_3 + n_4 + n_5 - n_6 - n_7 - n_8 - n_9$
3. If the state of tank T_n is *incL*, $incL^+$or $incL^-$ then G_3=2. If the state of tank T_n is *incS*, $incS^+$or $inc\ S^-$ then $G_3=1$. If the state of tank T_n is *std* then $G_3=0$.
4. If the number of open paths to the sink tank has been increased by n_{10}, then $G_4 = n_{10}$. If it has been decreased in n_{11}, then $G_4 = -n_{11}$. If it has remained constant, then $G_4 = 0$.

After this grading, a global grade is computed as for the NQA and used for choosing the action.

5. Comparing the agents with the human actions

The comparison is carried out on the basis of the sequence of actions performed by the human operator, performing the comparison at each sample instant. The absence of action is considered as a "no-action" action.

The test session is organised so that, at each time instant, the human and the artificial operator make a decision on the next control action and these actions can be compared directly. Each time instant hence provides a new experiment sample. The human operator action is always executed.

A comparison of the actions is performed sample by sample, and the final evaluation of how similar the reasoning of the two operators is, is obtained from the results on the whole experiment sample set.

In a preliminary step of the assessment, the human operator's reasoning is classified into a specific artificial agent's cognitive style of the library by means of a global distance (this issue is out of the scope of this paper).

This section assumes that the human operator's reasoning has been classified within the NQA (or QA) cognitive style and proposes a local distance, which can be used to measure the evolution of the human reasoning, given its cognitive style, over several sessions in time.

The two proposed artificial agents NQA and QA present a performance based on the concept of alarm and on the distinction between two situations, with and without alarms. In both cases, they have different strategies corresponding to different goals. Despite the global classification, an isolated human action can be inconsistent with these goals, (i.e. corresponding to non admissible actions as defined in sections 3.2.1.2 and 3.2.2.2). If the number of such "deviations" is above a given threshold, then a warning is returned indicating that the human behaviour should be classified within a different cognitive style (which may not be present in the library).

If the number of deviations does not reach the threshold, the human's reasoning is considered to fall within the agent's style and the comparison is performed on the samples corresponding to admissible actions. For the local distances the artificial agent behaviour must be taken as the reference. Hence, the action evaluation criteria must capture "how well" the instructions used in the artificial agent's decision making process are fulfilled by the performed action.

5.1 Case without alarms

The NQA and QA strategy is to accelerate the process by opening paths. In consequence, a human action that closes a valve is not an admissible action. For every admissible action, a grade G is associated, which is used to calculate the final distance assessing the comparison.

Let's define G_H as the human action grade and G_A as the artificial action grade.

The action of the artificial agent is graded $G_A = 0$, as it is taken as a reference. Note that the only cases that can happen are:

NQA action	Human action	Human action's grade
No-action	No-action	$G_H = 0$
Valve opened	Valve opened	$G_H = G_1$
Valve opened	No-action	$G_H = G_2$

table5: Human admissible action's gade

where G_1 and G_2 are obtained following the same criteria as used in the NQA strategy:

To compute G_1, define:

D = (minimum label[4] of the paths going through the human actioned valve) – (minimum label of the paths going through the NQA actioned valve).

If $D \neq 0$, then $G_1=D$.

If $D=0$, consider the k paths with minimum label and let $l+1$ be the number of equivalence classes defined by the *min-width* value ordered decreasingly. The class 0 includes the path(s) going through the valve actioned by the NQA. Assume that the path with maximum *min-width* going through the human actioned valve belongs to the *ith* equivalence class, then $G_1=i/l$.

In the case that the human operator does no action in spite of the existence of some closed valve, the grade is:

G_2 = 1+(maximum label among all the paths to T_n) – (minimum label of the paths going through the NQA actioned valve)

Note that $G_2 \geq G_1$. This satisfies the fact that, when there is some closed valve, the goal of accelerating the process makes it better to open any valve than to do nothing..

In the case $D \neq 0$, we have $0 \leq G_1 \leq \binom{n}{2}$, and in the case $D=0$, we have $0 \leq G_1 \leq 1$. With respect to G_2, we have $max\{1, G_1\} \leq G_2 \leq \binom{n}{2}$, where n, $n\geq3$, is the total number of tanks.

5.2 Case with alarms

The NQA and QA strategy is to come back to a non-alarming situation, while maintaining, with lower priority, the general objective of accelerating the process.

The global grade G [5]computed for selecting the action (Step 3 of section 3.2.2.2) is used.

As before, G_H is the human action grade and G_A is the artificial action grade.

Notice that for each action, the grades G_1, G_2, G_3, G_4 take their values in the following sets:

$-(n-2) \leq G_1 \leq 0$
$-(n-2) \leq G_2 \leq n-2$
$G_3 \in \{0,1,2\}$
$-n^* \leq G_4 \leq n^*$,

where n, $n\geq3$, is the total number of tanks and n^* is the maximum number of paths ending at T_n that can be opened all at once by opening one single valve. Hence,
$G= p_1G_1 +p_2G_2+p_3G_3+p_4G_4$ takes its value in $[x, y]$, with $x=-(n-2)(p_1+p_2) -p_4n^*$ and $y=p_2(n-2)+2p_3+p_4n^*$.

5.3 Comparison

The difference $|G_A(t) - G_H(t)| = D_t$ (G_A for the agent, G_H for the human), is computed for each human admissible action from $t = 1$ to $t=t_f$, where t_f is the instant defining the end of the test session (there is no more water in the intermediary tanks). Let t_{i1}, t_{i2},...,t_{im} be the instants

[4] This label refers to the label calculated in Step 2 of 3.2.1.2

[5] Recall that the grade G is obtained from four grades G_1, G_2, G_3 and G_4, corresponding to four goals, combined by a weighted sum.

corresponding to the human admissible actions. Hence, a vector $D=(D_{i1},...D_{im})$ is obtained. Each component of this vector takes values from 0 to $max\{y-x, \binom{n}{2}\}$

There are two natural ways of measuring the similarity between the performances of the human operator and the reference artificial operator, both in the form of a norm of the t_f-dimensional vector D:

$$d_1 = \sqrt{\frac{\sum_{j=1}^{m} \left(D_{t_{ij}}\right)^2}{m}} \qquad d_2 = \frac{\sum_{j=1}^{m} \left|D_{t_{ij}}\right|}{m}$$

These two distances come from two classical norms (the first one is the Euclidean norm) in R^m. They evaluate a kind of mean value over the m admissible experiment samples.

Although these distances are different, both of them varies from 0 to $max\{y-x, \binom{n}{2}\}-(x-y) = \gamma$. When $d_1 = d_2 = 0$ all the actions of the human operator coincide with the actions of the artificial agent, i.e. they have *identical behaviour.*

In order to interpret the results, the interval $]0, \gamma]$ is split up into four sub-intervals corresponding to the situations *"very similar behaviour"*, *"similar behaviour"*, *"different behaviour"*, and *"very different behaviour"*, as shown in figure 10:

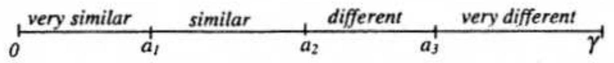

Figure 10: Reasoning comparison labels

where the thresholds a_1, a_2 and a_3, can be $\gamma/4$, $\gamma/2$ and $3\gamma/4$, or other values between 0 and γ chosen by the user.

Conclusion

This paper presents an on-going work, which provides the concepts and decision strategies for implementing qualitative artificial agents to be used as reference agents for assessing human reasoning in the process supervision domain. It is intended to contribute to the WAHRPS project, which is conducted by INSERM U455, in the medical domain for testing parkinsonian patients.

The paper builds on the observations that several concepts coming from the qualitative reasoning area of Artificial Intelligence match cognitive features outlined by psychologists and human factors' researchers about the way human operators perform the supervision task (causal mental models, qualitative anticipation, etc.)

It is our opinion that this research direction is a promising perspective although a lot of work still needs to be done.

The proposed agents (NQA and QA) are currently being implemented. This step will be followed by a series of tests on normal human subjects and the evaluation of the implemented cognitive styles in terms of their cognitive plausibility. These tests may show that the qualitative agents need some tuning of the perception model and control strategy parameters to envision a wider category of normal subjects. A set of variation qualitative agents may be necessary to cover the different categories, from humans with higher to lower skills.

References

Brown, R.G., and Marsden, C.D. 1991. Dual task performance and processing resources in normal Subjects and patients with Parkinson's disease. *Brain,* 114: 215-231.

Bousson, K and Travé-Massuyès, L. 1994. Putting more Numbers in the Qualitative Simulator CA-EN, *Int. Conf., on Intelligent Systems Engineering*, Hamburg-Harburg, Germany: 62-69.

Cellier, J; De Keyser, V and Valot,C. 1996. La gestion du temps dans les environnements dynamiques. Presses universitaires de France, Paris.

Cellier, J. and Mariné, C. 1991. Anticipatory Knowledge in a bus traffic traffic regulation task. *Quéinnec & Daniellou (Eds), Designing for everyone, vol. 3,* 93-94, London: Taylor and Francis.

Hoc, J.M. and Moulin, L. 1994 Rapidité du processus contrôlé et planifications dans un micro-monde dynamique. *L'Année Psycologique*, 521-552.

Kirwan, B. and Ainsworth, L.K. 1992. *A guide to task analysis.* London: Taylor and Francis.

Morris, N.M. and Rouse, W.B. 1985. The Effects of Type of Knowledge upon Human Problem Solving in a Process Control Task, *IEEE Transactions on Systems, Man & Cybernetics,* 15, 698-707.

Morris, N.M., Rouse, W.B and Fath, J.L. 1985. PLANT: an Experimental Task for the Study of Human Problem Solving in Process Control, *IEEE Transactions on Systems, Man & Cybernetics*, 15, 792-798.

Pasquet, B. 1995ª. Conception et réalisation d'une station de test du comportement d'un sujet réalisant la surveillance d'un système dynamique simple. Rapport de stage ingénieur ENSEEIHT, Toulouse.

Pasquet, B. 1995b. Simulation par réseau causal qualitatif d'un processus de surveillance optimal uilisé comme référence dans l'évaluation du raisonnement d'un opérateur humain. DEA Représentation de la Connaissance et Formalisation du Raisonnement, Université P. Sabatier, Toulouse.

Pastor, J.; Agniel, A. and Celsis, P. 1998. Artificial Reasoners for the Cognitive Assessment of Patients with Parkinson's Disease. *ECAI98, 13th European Conference on Artificial Intelligence,* H. Prade Ed., 119-123, John Wiley & Sons.

Travé-Massuyès, L; Dague, P. and Guerrin, F. 1997. *Le raisonnement qualitatif pour les sciences de l'ingénieur.* Ed. Hermes, Paris.

Woods, D.D.; O'Brien, J:F and Hanes, L.F. 1987.: *Human Factor Challenges in Process Control: the Case of Nuclear Power Plants.* Handbook of Human factors, 1724-1770, John Wiley & Sons.