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Abstract. In this paper we present a functional representation of human expert reasoning throughout its statements when assessing the condition of a given object. The human expert statements are represented as conjunctions of elementary propositions. We demonstrate that the conjunctions of elementary propositions can be represented as qualitative additions of qualitative functions in the *Q*-algebra (Q, $\approx$, $\oplus$, $\otimes$). We validate our functional representation by formalizing a representative human expert reasoning: assessment of dough condition in function with the ingredients characteristics.

Keywords. elementary proposition, qualitative algebra, qualitative functions, knowledge representation.

Introduction

The knowledge of human experts is in general incomplete since it does not cover the entirety of the search space of the close world studied. Confronted with a new problem in his domain of expertise, a human uses a reasoning that is implicit knowledge. With a functional representation of knowledge we could cover a possible entire search space in the close world studied. This allows the expert to explicit the search space, and if necessary by doing some experimental works. Dealing with incomplete knowledge or implicit knowledge that has not been yet elicited, is a situation a knowledge engineer has to face regularly. Approaches based on qualitative modelling methods have been designed to cope with those difficulties in Knowledge Based System building in the presence of incomplete knowledge [1, 2]. In their work on French breadmaking [3], Ndiaye et *al.* have introduced an approach aiming at representing expert reasoning in a homogeneous quantities space, through the use of characteristic cognitive operations. Then the authors translated the result in a qualitative algebra (*Q*-algebra).

In this paper we argue that the human expert statements are conjunctions of elementary propositions that can be represented as qualitative functions. Our real world problem is the one of the first operation of breadmaking process that consists in mixing all the ingredients to get the first dough. Experts need about twenty criteria to be able to predict the consistency of the dough resulting from this operation. Nevertheless, the

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knowledge elicitation phase has not allowed to deal with all the possible combinations of the input variables, which anyway are too numerous (about $1 \cdot 10^{13}$).

Our concern is to use the *Q*-algebra to prospect an articulation of the knowledge that allows the complete coverage of the combinations. To do this, we take advantage of the typical features of the reasoning of the experts involved in this study and the knowledge base already built. This approach is based on the locality principle proposed in [4]: *"Reasoning uses only part of what is potentially available (e.g., what is known, the available inference procedures). The part being used while reasoning is what we call context (of reasoning).".* With respect to this principle, a reasoning context is defined. The reasoning context is a mean to limit the investigation to what is really consistent with the existing. In a first section we recall the basic concepts of the *Q*-algebra, in the second section we describe the context of reasoning as a result of the existing, first textually, then translated in the *Q*-algebra. In the third section, given the context of reasoning, a hypothetic articulation of the knowledge is built, finally an application based on the actual knowledge base is described.

1. Background

1.1. Basics concepts of the Q-algebra

The qualitative algebra also called *Q*-algebra, aims at representing formally and managing heterogeneous and granular knowledge [3].

The calculus space is defined as a quantities space *Q* with seven elements: {vvl, vl, l, m, h, vh, vvh} strictly ordered. *Q* is representative of measurements defined in a continuous numerical scale in the set of real numbers divided into maximum of seven not clarified allied intervals (a partition). In the case of observation that cannot be measured, a discrete symbolic scale is used. The *Q*-algebra is defined through the 4-uple $(Q,\approx,\oplus,\otimes)$, with *Q* the quantities space, $\approx$ the qualitative equality, $\oplus$ and $\otimes$ respectively the qualitative addition and multiplication (Table 1) [3]. $\approx$ is reflexive, symmetrical, intransitive in the general case; $\oplus$ is commutative, associative, admits m as neutral element and admits the symmetrical element ($\forall x \in \boldsymbol{Q}, \exists x' \in \boldsymbol{Q}, x\oplus x' = x'\oplus x = \text{m}$); $\otimes$ is commutative, associative, admits h as neutral element, m as absorbing element, does not admit a symmetrical element and is qualitatively distributive compared to $\oplus$.

Table 1. Definition of the qualitative addition ($\oplus$) and multiplication ($\otimes$) in the $Q \cup$ {?} space [3]

$\oplus$	vvl	vl	l	m	h	vh	vvh	?
vvl	vvl	vvl	vvl	vvl	[vvl, vl]	[vvl, l]	?	?
vl	vvl	vvl	vvl	vl	l	m	[h, vvh]	?
l	vvl	vvl	vl	l	m	h	[vh, vvh]	?
m	vvl	vl	l	m	h	vh	vvh	?
h	[vvl, vl]	l	m	h	vh	vvh	vvh	?
vh	[vvl, l]	m	h	vh	vvh	vvh	vvh	?
vvh	?	[h, vvh]	[vh, vvh]	vvh	vvh	vvh	vvh	?
?	?	?	?	?	?	?	?	?

$\otimes$	vvl	vl	l	m	h	vh	vvh	?
vvl	vvh	vvh	vvh	m	vvl	vvl	vvl	?
vl	vvh	vvh	vh	m	vl	vvl	vvl	?
l	vvh	vh	h	m	l	vl	vvl	?
m	m	m	m	m	m	m	m	m
h	vvl	vl	l	m	h	vh	vvh	?
vh	vvl	vvl	vl	m	vh	vvh	vvh	?
vvh	vvl	vvl	vvl	m	vvh	vvh	vvh	?
?	?	?	?	m	?	?	?	?

2. The reasoning context

Knowledge used in French breadmaking is of causal type [3]. It is expressed through a set of propositions of relationships between one or more cause(s) and one effect.

This paper emphasises the first operation of the breadmaking process, the initial mixing. Experts use seventeen criteria to characterise the ingredients, and the dough condition after the mixing is characterised by its consistency. They are able to predict the value of the dough consistency from the seventeen criteria. However only a certain amount of all possible predictions of dough consistencies based on these seventeen criteria have been collected. The remaining predictions will be calculated given to the human experts for approval.

Therefore the question is "*How to take advantage of the knowledge base in its actual and incomplete form to prospect predictions in conditions not yet foreseen until now?*". The basic steps of the methods may be summarized as follows:

- identifying the knowledge expressed and the main features of the expert reasoning,
- deducing a formal reasoning context, specific to the close world studied,
- translating the knowledge, reasoning and context in the *Q*-algebra,

2.1. Description of the reasoning context

Knowledge already elicited is made of a set of propositions of causal relationships between the ingredients and the dough consistency. Propositions refer systematically to a processing standard, designed as "normal".

Characteristics of ingredients are measured or observed and the human experts interpret the measurement or observation in a qualitative space according to their effects on the dough consistency. The consistency of the dough is predicted in a qualitative space by human experts from the characteristics of the ingredients.

The human experts express consistency of the dough from a set of propositions, such as:

- *If the effect of each criterion is normal then the dough consistency is normal*
- *If the effect of the flour moisture content is very insufficient and the effects of the other criteria are normal then the dough consistency is very insufficient*
- *If the effect of the flour extraction rate is slightly insufficient and the effects of the other criteria are normal then the dough consistency is slightly excessive*
- ...

Each above-quoted proposition is an expression of a causal form, linking a conjunction of elementary propositions to the *dough condition*. It is common that experts express a judgement, a *dough condition* fault diagnosis or a *dough condition* prediction from elementary propositions, by assessing the gap between the *dough condition* and a standard *dough condition* said normal. This observation leads to define the notions of elementary proposition, *dough condition* and normality.

Definition 1. An elementary proposition (*pe*) is unary: it links the effect of a criterion and a value in a qualitative space.

Note that criteria are defined in the set of all real numbers or in a vocabulary space. The following example is elementary proposition:

The effect of the flour moisture content is very insufficient;

with *flour moisture content* the criteria and *very insufficient* the linked value in a qualitative space.

The elementary propositions are instances of the effects of the criteria. For a criterion *i*, pe_{ij} designates the j^{th} instance of the effect of the i^{th} criterion, with *i* and *j* natural positive numbers $(i, j \in \mathrm{N}, i \geq 1 \wedge j \geq 0)$.

Definition 2. The *dough condition* (*ep*) is *n-ary*, with *n* the total number of descriptive criteria of the ingredients, which are elementary propositions.

The instances of the *dough condition*, which represent the possible conditions of the dough (*ep*) after the "initial mixing", will be noted pe_k, with *k* a positive natural number, $(k \in \mathrm{N}, k \geq 0)$.

Definition 3. An elementary proposition or a *dough condition* is said normal if its value is optimal compared to the processing goal.

Dough consistency is normal if it is optimal in relation with the breadmaking operation that follows, i.e. dough-making. This optimum state is reached when an optimal compromise between the effects of the criteria is achieved; for each criterion, its normal value is its compromise value. Thus, an elementary proposition is normal if its value corresponds to the optimal effect of the criterion regarding the normal *dough condition*. ep_0 designates the normal instance of the *dough condition* and pe_{i0} the normal instance of the effect of the criterion *i*.

$$pe_{10} \wedge \ldots pe_{n0} \rightarrow ep_0 \qquad (1)$$

The proposition "*If the effect of each criterion is normal then the dough consistency is normal*" implies that if the effects of all the criteria are not normal then the *dough condition* may be normal or not: therefore the effects of the criteria influence the *dough condition*.

Definition 4. A criterion i influences the *dough condition* if, for at least one of its instances of its effect, pe_{ij} with $j \geq 1$, being not-normal and the effects of the others criteria being normal, the *dough condition* differs from its normal value.

$$pe_{10} \wedge \ldots pe_{ik} \wedge \ldots pe_{n0} \rightarrow ep_j \qquad (2)$$

with *k* a natural number strictly superior to zero and ep_j the values of the dough condition. This definition has the following consequence: the contribution of a given criterion is expressed through the value of the *dough condition* when the criterion takes successively the different values of its domain and the other criteria are normal.

Example. *If the effect of each of the determination criterion of the dough consistency is normal except the one of the flour moisture content then:*

- *if the effect of the flour moisture content on the dough consistency is excessive then the dough consistency is excessive*
- *if the effect of the flour moisture content on the dough consistency is insufficient then the dough consistency is insufficient*

Generally speaking we may state the following axiom:

Axiom 1. Given *n* criteria having an effect on the *dough condition*, the conjunction of *n* *pe* referring to the *n* criteria is necessary and sufficient to predict *ep,* the value of the *dough condition*.

$$pe_{1j} \wedge \ldots pe_{nk} \rightarrow ep_i \qquad (3)$$

By the way, it appeared clearly during the knowledge elicitation sessions that the experts make the effect of a criterion vary one by one, so that they can subsequently build combinations of several effects of criteria and consider their influence on the *dough condition*. This cognitive process is summarized by the two following axioms:

Axiom 2. To formulate a prediction, human experts reason in one dimension, they assess the effect of the criteria one by one.

Axiom 3. The experts formulate a prediction by assessing the deviations from a standard. This standard is a normal state seen as optimal with respect to an objective.

The knowledge base is, at this stage of the work, made of assertions such as "*If the effect of the flour moisture content on the consistency is very insufficient and the effects of the other criteria are normal, then the consistency is very insufficient*". These propositions express the effect of a criterion, here the flour moisture content, on the *dough condition*, characterised here by its consistency. The human expert reasoning is then hypothetico-deductive, it aims at linking an instance of the dough condition to a set of elementary propositions (Figure 1).

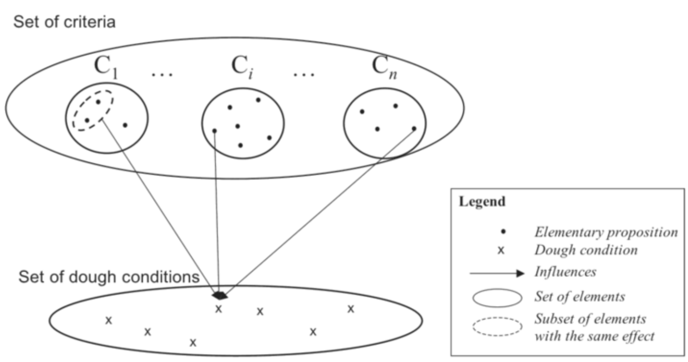

Figure 1. And/or graph showing the problem of *dough condition* assessment from t-uple of n criteria.

Our objective is to represent such expert reasoning process in the *Q*-algebra in narrowing the investigation domain with respect to the reasoning context previously defined.

3. Prospecting the prediction of consistency

3.1. Qualitative analysis of expert's interpretation

Measurements or observations of criteria are translated in a qualitative scale with a maximum of seven levels. For example the flour moisture content is insufficient if the content is inferior to 13%, average if it is between 13% and 15.5% and excessive if it exceeds 15.5%. The experts in breadmaking assess qualitatively the criteria with respect to a processing standard. Their rating scale goes from very insufficient to very excessive compared to the standard. The rating scale is made of seven elements (Table 2). The effects of each criterion on the *dough condition* are assessed with respect to a normal *dough condition*. For instance, the effect of the flour moisture content is very insufficient if the flour moisture content is excessive, normal if the moisture content is average and very excessive if the flour moisture content is insufficient.

Table 2. Rating scale of criteria and dough condition

Expert judgment	Example of interpretations	
very excessive	very high	very strong
excessive	high	strong
slightly excessive	slightly high	slightly strong
average	normal	perfect
slightly insufficient	slightly low	slightly weak
insufficient	low	weak
very insufficient	very low	very weak

3.2. Translation in the Q-algebra of the reasoning context

The *Q*-algebra implies to work within the *Q* quantities space of seven symbolic elements. This space makes it possible to represent the scale of expert. The operations defined in this space make it possible to represent in functional form the relations between the criteria and their effects. Measurements and observations of the criteria as well as the *dough condition*s are translated in *Q* via the scale of expert (Table 3). The relation between a criterion and its effects is represented in the form of a qualitative function and, otherwise, in the form of an *ad hoc* truth table (Table 4).

Table 3. Translation of the scale of expert in the Q quantities space

Scale of expert	Translation in Q
very insufficient	vvl
insufficient	vl
slightly insufficient	l
normal	m
slightly excessive	h
excessive	vh
very excessive	vvh

Table 4. Translation in the Q-algebra of the flour moisture content (mc) criterion, its effects and the relation which binds it to its effects

Flour moisture content (x)			The effect of flour moisture content on the dough consistency (y)		Qualitative function ($y = f(x)$) effect in function with the criterion in Q
measurement (mc)	assessment in the scale of expert	translation in Q	assessment in the scale of expert	translation in Q	
mc < 13%	insufficient	l	very excessive	vvh	
13≤mc≤15.5%	average	m	normal	m	$y = \text{vvl} \otimes x$
mc > 15.5%	excessive	h	very insufficient	vvl	

In [3], two particular truth tables have been defined in the Q-algebra $\top(x)$ and $\bot(x)$:

x	vvl	vl	l	m	h	vh	vvh	?
$\top(x)$	vvl	vl	l	m	m	m	m	?
$\bot(x)$	m	m	m	m	h	vh	vvh	?

In this work the general form of qualitative functions is as below:

$$f(x) = a_1 \otimes \top(g(x)) \oplus b_1 \otimes \bot(h(x)) \oplus c_1 \qquad (4)$$

with

$$g(x) = a_2 \otimes \top(x) \oplus b_2 \otimes \bot(x) \oplus c_2$$
$$h(x) = a_3 \otimes \top(x) \oplus b_3 \otimes \bot(x) \oplus c_3$$
$$a_1, b_1, c_1, a_2, b_2, c_2, a_3, b_3, c_3 \quad \text{constants in } Q$$

let us note that for $a_2 = b_2$

$$g(x) = a_2 \otimes (\top(x) \oplus \bot(x)) \oplus c_2 = a_2 \otimes x \oplus c_2$$

which is of the same form as $y = a \otimes x \oplus b$. This report is also true for $h(x)$ when $a_3 = b_3$ and for $f(x)$ when $a_1 = b_1$ and $g(x) = h(x) = x$.

3.3. Notation

In the Q quantities space we will note:

m the average value in the scale of expert, the normal effect of a criterion on the *dough condition* and the normal *dough condition*.

In the *Q*-algebra we will note:

x_i the criterion *i*

y_{i0} the normal effect of the criterion *i* on the *dough condition*, $y_{i0} = \mathsf{m}$

y_i the effect of the criterion *i* on the *dough condition*, $y_i \in Q$, $i \le 7$

$f_k(x_i) = y_i$ the function that binds a criterion to its effect on the *dough condition*

z_0 the normal *dough condition*, $z_0 = \mathsf{m}$

z the *dough condition*, $z \in Q$

Since, by axiom 1, the conjunction of the criteria having an effect on the *dough condition* is necessary and sufficient to evaluate the latter, we assume the following hypothesis:

Hypothesis. *The conjunction of the criteria having an effect on the dough condition is necessary and sufficient to evaluate this last*.

From this hypothesis the following theorem is derived in the *Q*-algebra:

Theorem. The dough condition is qualitatively equal to the qualitative addition of the effects of the criteria.

$$\forall x_1,\dots x_n \in Q, z \approx f_k(x_1) \oplus \cdots f_p(x_n) \qquad (5)$$

Proof. If we replace in equation (5) the qualitative addition operator (⊕) by the qualitative multiplication operator (⊗) then equation (5) becomes:

$$\forall x_1,\dots x_n \in Q, z \approx f_k(x_1) \otimes \cdots f_p(x_n) \qquad (6)$$

As m is the absorbing element of the ⊗ operator then

$$\forall x_1,\dots x_{i-1}, x_{i+1},\dots x_n \in Q, \exists x_i \in Q \middle| f_k(x_i) = \mathsf{m}$$
$$\Rightarrow z \approx f_p(x_1) \otimes \cdots f_q(x_{i-1}) \otimes \mathsf{m} \otimes f_r(x_{i+1}) \otimes \cdots f_s(x_n) = \mathsf{m}$$

the only fact that $f_k(x_i)$ is equal to m would be thus sufficient so that *z* is equal to m, what is in contradiction with axiom 1; considering the operators of the *Q*-algebra (*Q*, ≈, ⊕, ⊗), the conjunction is here a qualitative addition; that we will check on equations (1) and (2):

The equation (1) is rewritten in the *Q*-algebra

$$\exists x_1,\dots x_n \in Q \middle| f_p(x_1) = \cdots f_s(x_n) = \mathsf{m}, z_0 \approx f_p(x_1) \oplus \cdots f_s(x_n) = \mathsf{m}$$

what is validated because m is the neutral element of the ⊕ operator and then ($\mathsf{m} \oplus \mathsf{m} = \mathsf{m}$).

The equation (2) is rewritten in the *Q*-algebra

$$\forall x_i \in Q, \exists x_1, \ldots x_{i-1}, x_{i+1}, \ldots x_n \in Q \middle| f_p(x_1) = \cdots f_q(x_{i-1}) = f_r(x_{i+1}) = \cdots f_s(x_n) = \mathsf{m},$$
$$z \approx f_k(x_i)$$

what is validated because m is the neutral element of the ⊕ operator and then

$$\mathsf{m} \oplus \cdots \mathsf{m} \oplus f_k(x_i) \oplus \mathsf{m} \oplus \cdots \mathsf{m} = f_k(x_i).$$

4. Results

We applied this prospective approach to the calculation of the dough consistency on the basis of a knowledge base which contains seventeen criteria and their respective contributions on consistency. This knowledge was translated in the *Q* quantities space as illustrated in table 5.

Table 5. Examples of translation of knowledge in the *Q*-algebra

Criterion	Measurement or observation	Translation in *Q* (x_i)	Effect on consistency (y_i)	Qualitative function
Flour moisture content (mc)	mc < 13%	l	vvh	$y_1 = \mathsf{vvl} \otimes x_1$
	13% ≤ mc ≤ 15.5%	m	m	
	mc > 15.5%	h	vvl	
Flour extraction rate (er)	er < 75%	l	l	$y_2 = x_2$
	75% ≤ er ≤ 80%	m	m	
	er > 80%	h	h	
Rate of fatty acid (fa)	fa ≤ 0.4%	m	m	$y_3 = \mathsf{m}$
	fa > 0.4%	h	m	
Flour protein content (pc)	pc < 10%	l	vl	$y_4 = \mathsf{vh} \otimes \top(x_4) \oplus \mathsf{vvh} \otimes \bot(x_4)$
	10% ≤ pc ≤ 12%	m	m	
	pc > 12%	h	vvh	

In the examples of table 5, y_3 illustrates a criterion which does not have any effect on consistency, y_1 illustrates a criterion which has an inversely proportional effect and y_2 and y_4 illustrate each one a proportional effect (Figure 2).

In a context where the criteria would be limited to those of table 5, we would have:

$$z = y_1 \oplus y_2 \oplus y_3 \oplus y_4$$
$$z = \mathsf{vvl} \otimes x_1 \oplus x_2 \oplus \mathsf{m} \oplus \mathsf{vh} \otimes \top(x_4) \oplus \mathsf{vvh} \otimes \bot(x_4)$$
$$z = \mathsf{vvl} \otimes x_1 \oplus x_2 \oplus \mathsf{vh} \otimes \top(x_4) \oplus \mathsf{vvh} \otimes \bot(x_4)$$
$$z = y_1 \oplus y_2 \oplus y_4$$

For $y_1 = y_2 = y_4 = \mathsf{m}, \quad z = \mathsf{m} \oplus \mathsf{m} \oplus \mathsf{m} = \mathsf{m}$
and for $y_2 = y_4 = \mathsf{m}, \quad z = y_1 \oplus \mathsf{m} \oplus = y_1$

The above equations show that x_3 has no effect on z, that means that the rate of fatty acid has no effect on the dough consistency. This is already known by the human experts but not explicitly expressed. The functional representation of knowledge facilitates significantly the knowledge handling, it makes possible to explicit some implicit knowledge as in this example.

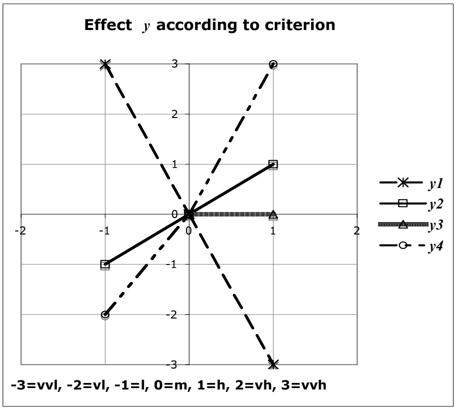

Figure 2. Variations of the effects of the criteria of table 6 according to the qualitative values of the criteria

This functional approach of the representation of expert knowledge makes it possible to find computed values ($z_{\text{calculated}}$) where human experts do not have the expertise yet (Table 6). The experts will then have the possibility to perform experiments to validate or to cancel the calculated results and thus to extend the available knowledge. Another important possibility allowed by the functional representation of knowledge is that we can pose a qualitative equation to solve it and then to establish the conditions when the two functions are qualitatively equal.

Table 6. Result of the theorem ($z_{\text{calculated}}$) confronted with the result of the collection of knowledge (z_{expert}). In bold characters the agreements between the expertise and calculation, in frame the normal consistency.

x_1	x_2	x_4	y_1	y_2	y_4	$z_{\text{calculated}}$	z_{expert}
m	l	l	m	vvh	l	[vh, vvh]	?
m	**l**	**m**	**m**	**vvh**	**m**	**vvh**	**vvh**
m	l	h	m	vvh	h	vvh	?
m	**m**	**l**	**m**	**m**	**l**	**l**	**l**
m	**m**	**m**	**m**	**m**	**m**	**m**	**m**
m	**m**	**h**	**m**	**m**	**h**	**h**	**h**
m	h	l	m	vvl	l	vvl	?
m	**h**	**m**	**m**	**vvl**	**m**	**vvl**	**vvl**
m	h	h	m	vvl	h	[vvl, vl]	?

The statement of a hypothesis allows us to implement the corresponding knowledge base system using the *QualiS*© expert system shell [5]. By this way we are able to present the outputs to experts in their natural language (Figure 3).

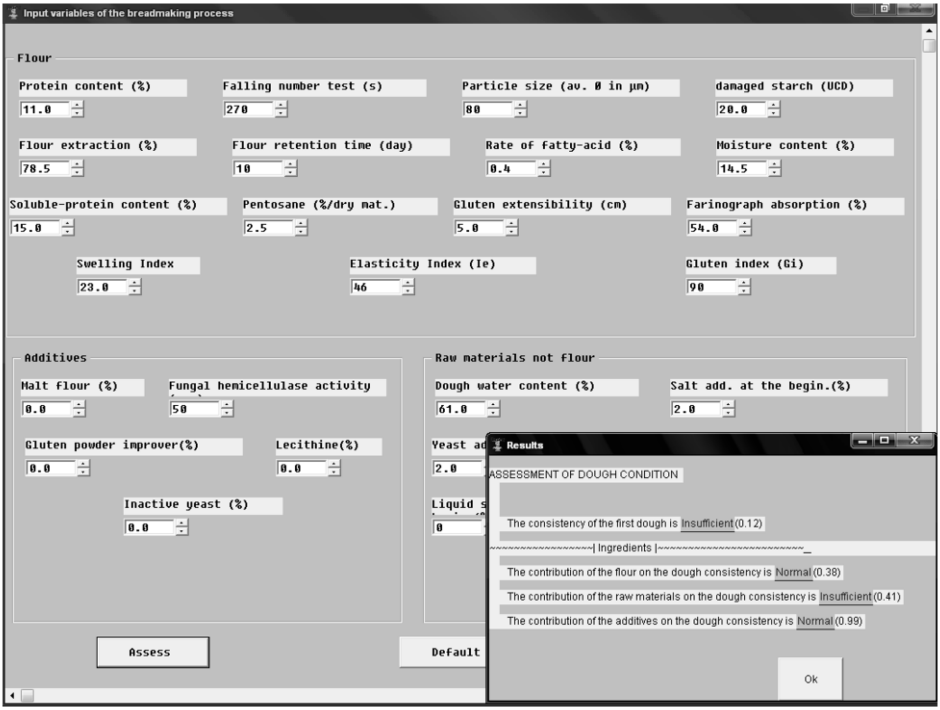

Figure 3. Mock-up implemented using the *QualiS*© expert system shell

5. Related works

This work extends the representation of knowledge for expert systems [6] by using a qualitative functional representation via the *Q*-algebra. In some cases it could be possible that a functional representation of a relation between some variables is not possible; Ndiaye et *al.* [3] proposed the use of ad-hoc decision tables to represent them in the *Q* quantities space. The quantities space with the seven elements {vvl, vl, l, m, h, vh, vvh} has been defined by Guerrin [7] as a strictly ordered set of symbols with two basic functions, *pred* (predecessor) and *suc* (successor). Ndiaye et *al.* [3] used this quantities space as the domain of values, *Q*, of their *Q*-algebra. The qualitative equality, addition and multiplication are well described in the literature on signs algebra that is based on a three elements quantities space {-, 0, +} [8, 9, 10, 11]. The main differences between the signs algebra and the *Q*-algebra lie in the facts that: i/ the seven numbers of elements increase the difficulty of the qualitative calculus, ii/ the functions in the *Q*-algebra are used to calculate the value of a variable in *Q*, whereas the functions in the signs algebra calculate the sign of a variable, the direction of its slope in time [1].

6. Conclusion and future works

In this paper we have introduced an original method to represent, as qualitative functions, the human expert knowledge and the reasoning it contains. We have shown how the definition of a reasoning context allows us to prospect the knowledge not yet elicited. Such an approach is a mean to complete the domain of a given state variable especially when several antecedents may vary concomitantly. The entire possible search space, about 1.10^{13} combinations of inputs, is covered by the implemented mock-up. The reviewing of the results by the experts is a work currently in hand based on an adapted strategy. One may expect that the results from the validation process leads to the refinement of the elicited knowledge and their functional representation in the *Q*-algebra. We believe that our approach will be applicable to all systems based on knowledge production rules with independent variables.

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