

# **A quantitative analysis of the robustness of knowledge-based systems through degradation studies**

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**Abstract.** The overall aim of this paper is to provide a general setting for quantitative quality measures of knowledge-based system behaviour that is widely applicable to many knowledge-based systems. We propose a general approach that we call degradation studies: an analysis of how system output changes as a function of degrading system input, such as incomplete or incorrect data or knowledge. To show the feasibility of our approach, we have applied it in a case study. We have taken a large and realistic vegetation-classification system, and have analysed its behaviour under various varieties of incomplete and incorrect input. This case study shows that degradation studies can reveal interesting and surprising properties of the system under study.

**Keywords:** Quantitative analysis; Knowledge-based systems; Robust behaviour; Validation

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## **1. Motivation**

When asked about the essential differences between knowledge-based systems (KBSs) and conventional software, one often hears the claim that KBSs can deal with incomplete, incorrect and uncertain knowledge and data, whereas conventional software is typically very brittle in these respects (see e.g., Hayes-Roth (1984) for a very early formulation of this claim). Although, nowadays researchers no longer view this distinction as either necessary or sufficient to define a KBS, it is believed that the ability of KBSs to deal with missing or invalid data is an essential dimension of KBS validation.

There have been both practical experience and theoretical analysis over many years to back the mentioned claim. As an example of practical experience, Preece et al. (1997) reports that, in a number of verification exercises, errors were found

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*Received 29 November 2002*

*Revised 21 May 2003*

*Accepted 8 July 2003*

*Published online 8 April 2004*

in the knowledge-base of KBSs, which were nevertheless still functioning at acceptable levels. As an example of theoretical analysis, ten Teije and van Harmelen (1996, 1997) prove that, for a large class of diagnostic systems, the computed set of diagnoses degrades gracefully and predictably when either the system input (observations) or the knowledge-base degrades in quality.

However, until now, the analysis of the robustness of KBSs in the face of incomplete, incorrect or uncertain knowledge and data has been limited to such practical experience and qualitative analysis. Little or no attempt has been made at a quantitative analysis of the proclaimed robustness of KBSs. A recent special issue of a journal was dedicated to methods for evaluating KBSs (Menzies and van Harmelen 1999). None of the papers in that special issue performed any quantitative analysis on the quality of KBSs. The editorial of this special issue lists only a handful of quantitative evaluation studies that have been performed over a decade or more of KBS research. In fact, one paper in that special issue (Shadbolt et al. 1999) even seems to suggest that global qualitative evaluations are about as much as we can expect from KBS evaluation projects. Finally, one of the reviewers of this paper even remarked: "for a long time, the KA community has decried the lack of good evaluation metrics to measure the quality of the KA process and of the resulting knowledge bases." We consider this a serious defect in the study of KBSs, particularly because such robustness is often proclaimed as a unique characteristic of KBSs.

The aim of this research is to show that *a quantitative analysis of the robustness of KBSs is both possible and useful*. To argue this claim, we present a case study in which we perform such a quantitative analysis for a particular KBS. In Sect. 2, we describe our approach to measuring robustness by degradation studies, and we give definitions for the basic notions involved in such degradation studies. In subsequent sections, we apply this approach in a case study. Section 3 describes the KBS that we subjected to a degradation study. Section 4 gives an overview of the degradation studies we performed. Thereafter, Sect. 5 reports our robustness results with respect to the data input and Sect. 6 the robustness results with respect to the knowledge base used. The results obtained will be analysed in these two sections. Finally, Sect. 7 summarizes the main points of the paper and, in Sect. 8, we look at future steps to be taken.

## 2. Approach and foundational definitions

In this section, we describe our approach to measuring robustness by degradation studies and we give definitions for the basic notions involved in such degradation studies. Our aim is to define a very general set of notions that can be widely used in future degradation studies. We regard this section as the central contribution of this research: the definitions in this section should form the basis of similar analyses by other researchers and practitioners.

### 2.1. Robustness and degradation

The IEEE Standard Glossary of Software Engineering Terminology (IEEE 1990) gives the following definition for robustness:

**Informal Definition 2.1 (Robustness).** The degree to which a system or component can function correctly in the presence of invalid inputs or stressful environmental conditions.

In other words, robustness of a KBS is concerned with the way in which the quality of the KBS output degrades as a function of a decrease in the quality of the KBS input. This definition immediately leads to the idea of degradation studies:

**Informal Definition 2.2 (Degradation study).** In a *degradation study*, we gradually decrease the quality of the KBS input and measure how the KBS output quality changes as a result.

This informal definition contains the concepts of ‘KBS input (quality)’ and ‘output quality,’ which we will discuss in more detail in the Sects. 2.2 and 2.3.

## 2.2. Output quality

Of course, we must be more precise about the rather vague notion of quality of the KBS input and output. Concerning the KBS output, we assume that this is always a *set* of answers. In fact, for many typical KBS tasks, this is a realistic assumption: a set of consistent classes in a classification task, a set of likely hypotheses in a diagnostic task, a set of potential designs in a configuration task, etc.<sup>1</sup> More explicitly stated:

**Assumption 2.1.** For the KBSs that we consider, we assume that their output can be interpreted as a discrete set of answers.

Under this assumption, we define two measures for KBS output quality. Let  $correct(I)$  be the set of all correct answers for a given input  $I$ , and  $output(I)$  be the set of actually computed answers for a given input  $I$ .

**Definition 2.1 (Recall).** The  $recall(I)$  of a KBS for a given input  $I$  is defined as:

$$recall(I) = \frac{|correct(I) \cap output(I)|}{|correct(I)|}.$$

In other words, the recall is the fraction of correct answers that the system actually computes. It can, of course, happen that  $correct(I) = \emptyset$ , i.e., there is no correct answer. For example, this happens when the system is presented with a case  $I$  for which no correct output exists, such as an inconsistent set of observations for a classification system or an inconsistent set of requirements for a design system. In this case we define:

$$\text{if } correct(I) = \emptyset \text{ then } recall(I) = 1,$$

as all correct answers are recalled by the system.

**Definition 2.2 (Precision).** The  $precision(I)$  of a KBS for a given input  $I$  is defined as:

$$precision(I) = \frac{|correct(I) \cap output(I)|}{|output(I)|}.$$

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<sup>1</sup> Of course, even for KBSs that return a single answer, this assumption still holds because we can interpret such a single answer  $x$  simply as the singleton set  $\{x\}$ .

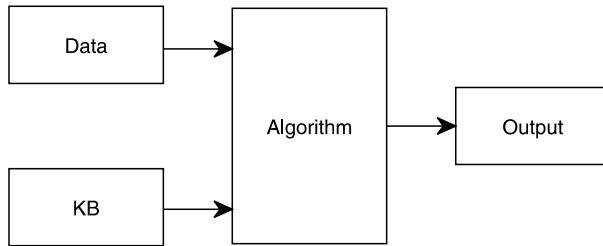


Fig. 1. Knowledge-based system components

In other words, the precision is the fraction of computed answers that are actually correct. In the case  $output(I) = \emptyset$  (i.e., the system returns no output), we define:

$$\text{if } output(I) = \emptyset \text{ then } precision(I) = \begin{cases} 1 & \text{if } correct(I) = \emptyset, \\ 0 & \text{otherwise.} \end{cases}$$

This reflects the intuition that the only correct output in this case is no output at all.

Ideally, both recall and precision would be 1 (i.e., the system returns all and only correct answers) but, in practice, they are antagonistic: a higher precision (recall) is usually paid for with a lower recall (precision).

There are two attractive aspects to these definitions for measuring the output quality. First, these definitions are well known from the literature on information retrieval (e.g., Salton and McGill 1983) and have proven to be useful, informative and intuitive measures in many studies in that field and elsewhere (see, for instance, Schumann and Fischer (1997) for an application of these measures to deduction-based software component retrieval). Second, these measures are completely general and make no commitment to either the task or the domain of the KBS that we wish to study. Consequently, the approach proposed can be directly applied to other KBSs, even when they are very different from the one that we happen to have chosen in our own case study.

The above definitions are in fact gradual versions of the classical notions of soundness and completeness: recall corresponds to the degree of completeness of the system and precision corresponds to the degree of soundness of the system. These measures provide a quantitative angle on earlier work by van Harmelen and ten Teije (1998), which was strictly qualitative.

### 2.3. Knowledge-based system input

We can represent a KBS graphically as in Fig. 1: the data, the knowledge base, the algorithm and the output. By KBS input, we mean the data given for example by a user as well as the knowledge base used by the system. The degradation experiments we propose for measuring the robustness of the system will either be with respect to the quality of the data input or with respect to the quality of the knowledge base.

For the input quality measure, we give two general aspects to consider for measurement. These aspects are incompleteness or incorrectness of the data or knowledge. Although these aspects are quite general, they may not be applicable to every knowledge base. The aspects proposed also do not cover all possible aspects one might

want to measure. More explicitly formulated, with incompleteness and incorrectness, we mean the following:

**Incomplete:** A part of the data input or part of the knowledge used is missing from the KBS input. For example, the data input could be a number of observations. Some of the observations might be too hard or too expensive to obtain. A part of the knowledge might be missing because the knowledge was obtained from human experts who forgot to provide it.

**Incorrect:** In contrast with incomplete data or knowledge, a certain part of the data or knowledge *is* provided by a user or expert. However, it is incorrectly represented. For example, incorrect data could be caused by a user who has made a wrong observation. Incorrect knowledge could, for example, be caused by faulty knowledge of an expert, misunderstandings when coding the knowledge into the system or limitations of the representation used by the system.

These two aspects are important in KBS validation. For example, a knowledge base will most likely be incomplete and often partially incorrect. Hence, to analyse the robustness of a knowledge base with respect to incompleteness or incorrectness is a realistic and important issue.

Notice that we have already taken a step further than van Harmelen and ten Teije (1998). In that paper, the authors did not commit to any definition of quality on input or output, and only demanded that whatever the definition was, it should respect a partial ordering. In our approach with degradation testing, we commit to a specific definition of output quality while leaving input quality open to be defined for each specific application.

## 2.4. Comparing robustness

The only notion that is still left undefined is some ordering on robustness: when do we call a system more robust or less robust than another? Unlike output quality (where we have given a single widely applicable definition) and input quality (the definition of which is deliberately left open to depend on the task type), we have not been able to determine a good answer to this question.

When input quality decreases, a system that produces an output with a fluctuating quality is much less predictable than a system that produces an output with a monotonically decreasing quality. We therefore demand that any system that is called robust at least produces an output with monotonically decreasing quality as a function of decreasing input quality.

**Definition 2.3 (Monotonicity).** A robust system will show a monotonically decreasing output quality as a function of deteriorating input quality.<sup>2</sup>

Note that this demand corresponds precisely to the usual demand on anytime algorithms that their output quality monotonically increases with increasing run time (Dean and Boddy 1988). However, this demand is insufficient for ordering various systems according to their robustness. We therefore give additional competing definitions without choosing one over the other.

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<sup>2</sup> In practise, this demand may be a bit too strong. Systems that produce a more or less monotonic output can also be considered robust.

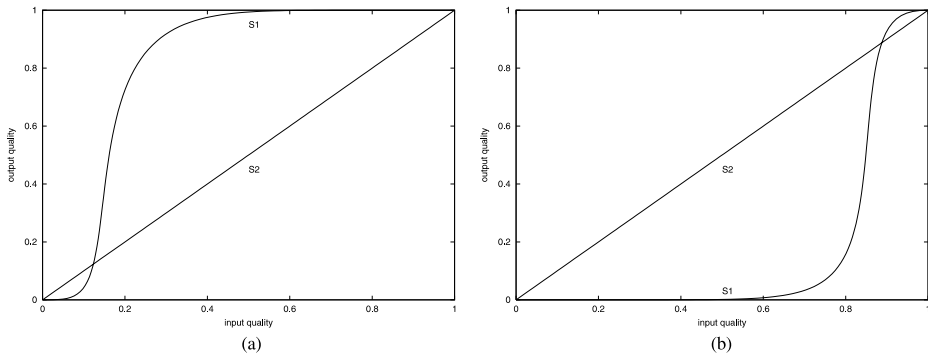


Fig. 2. Comparing robustness of systems

**Definition 2.4 (Quality value).** A system  $S_1$  is more robust than a system  $S_2$  for a set of inputs if, everywhere on that input set, the output quality of  $S_1$  is higher than the output quality of  $S_2$ .

**Definition 2.5 (Rate of quality change).** A system  $S_1$  is more robust than a system  $S_2$  for a set of inputs if, everywhere on that input set, the output quality of  $S_1$  decreases more slowly than the output quality of  $S_2$ .

**Definition 2.6 (Integral of quality value).** A system  $S_1$  is more robust than a system  $S_2$  for a set of inputs if, on that input set, the integral of the output quality of  $S_1$  is larger than the same integral for  $S_2$ .

Formally speaking, Definition 2.4 compares the output quality of two systems (and is concerned with which system produces the *best* output), while Definition 2.5 compares the first derivative of the output quality of the systems (and is therefore concerned with which system produces the *most stable* output). Definition 2.6 compares the overall quality of the output quality over an entire interval even when neither system always dominates the other (as required in Definition 2.4). These definitions are illustrated in Fig. 2.<sup>3</sup>

Note that the definitions do not have to be applied on the entire input quality range. Instead, they should be applied to an interval of interest. Usually, this will be some interval including 1 (i.e.,  $[x, 1]$ ).

In Fig. 2a, system  $S_1$  is more robust on, for example, the interval  $[0.1, 0.3]$  according to Definition 2.4 because, on that interval, its output quality is always higher than that of  $S_2$ . However, according to Definition 2.5,  $S_2$  is the more robust of the two because its output quality decreases more gradually (reading the graph from right to left). Definition 2.6 allows us to take a more overall perspective: it takes the size of the area under the output quality graph as a measure of the overall quality. Under this definition,  $S_1$  is more robust on the entire interval  $[0, 1]$  because the value of  $\int_0^1 \text{output quality } d(\text{input quality})$  is larger for  $S_1$  than for  $S_2$ . Note that the situation is rather different in Fig. 2b. Although the output quality again

<sup>3</sup> In our figures, we plot input quality against output quality. When speaking about robustness, we are interested in *decreasing* input quality, so the graphs must be read from right to left.

increases monotonically from 0 to 1 over the same interval, the comparisons between  $S_1$  and  $S_2$  on various subintervals are very different. Now, for example, on the interval  $[0.1, 0.3]$ ,  $S_2$  is more robust than  $S_1$  when using Definition 2.4, but  $S_1$  is more robust than  $S_2$  when using Definition 2.5.

At the current point in our research, we simply propose each of these definitions as reasonable, without claiming superiority of any definition in all cases. In fact, we believe that, under different pragmatic circumstances, different definitions will be preferable: if steep drops in system performance are to be avoided, the second definition is preferable. If one is interested in upholding output quality as long as possible in the face of declining input, the other two definitions may be preferred.

### 3. Example knowledge-based system

For our case study, we have used a classification system for commonly occurring vegetation in Southern Germany. The plant-classification system was created with the D3 Shell-Kit, which is a tool for the development of KBSs. We will not discuss this tool here but refer to a number of publications about D3 (Puppe et al. 1994, 1996). It is also possible to download a demo version of the software from the URL <http://d3.informatik.uni-wuerzburg.de>.

The plant-classification system that we studied can have 40 different observables as input and has 93 different plant names as output. The knowledge base consists of 7,586 rules. Furthermore, with the system, we received 150 test cases. Each of these cases consisted of the set of observations for that case (color and shape of flowers, leaves, stem, etc.), together with the (supposedly correct) answer for these observations as given by a human expert. Around 97% could be answered correctly by the system.

The input observations can be entered in a graphical user interface, but the user is not restricted to the ordering in this interface. The observations can be entered in any order, thus the input can be seen as a *set*. This is not entirely true because some observations are dependent on other observations and will only appear when certain input conditions are met. Because of these dependencies, the maximum number of observations that can be given for one case is 30.

For our degradation tests, we translated the plant classification system into Prolog code. This resulted in a knowledge base with 11,724 rules, all with the following representation:

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kb(Plant, Observation, Value, Score).
```

Each time a new observation is given to the system, all rules are collected containing the same *Observation* and *Value*. For each of these rules, the score of the *Plant* mentioned in the rule is adjusted by adding the *Score* to its current score. When the score crosses a threshold, it is output by the system.

In fact, the rules do not actually contain numerical scores but descriptions, which were used to make it easier for the experts to express their knowledge. The descriptions are, however, translated to numerical scores whenever they are used by the system. We will therefore use the descriptions as if they are numbers. The descriptions range from  $P_1$  through  $P_6$  for positive scores and  $N_1$  through  $N_6$  for the negative scores. Furthermore,  $|P_i| = |N_i|$  for  $i = 1, \dots, 6$  and  $P_{i+1} = 2 * P_i$  for  $i = 1, \dots, 5$ .

## 4. The degradation studies

In the following sections, we will report our robustness analysis of the plant classification system. In Sect. 5, we will analyse the robustness with respect to the data input, while in Sect. 6, we will analyse the robustness with respect to the knowledge base used.

Before discussing the results in more detail, we emphasize that the case study only serves to illustrate our proposal to analyse the robustness of KBSs through degradation studies. The important aspects of this case study are the quantities measured and how they were analysed, not the obtained robustness results of the plant classification system.

Before we discuss the results, a final remark must be made about the possible values of recall and precision in this case study. Because, for every case, there is at most one correct answer (namely the name of the actual plant on which the observations were made), we have for any case  $I$ ,  $|correct(I)| = 1$  iff the case is in the knowledge base or  $|correct(I)| = 0$  iff the case is not in the knowledge base. As a result, the only values that  $recall(I)$  can assume are either 0 or 1. For the same reason,  $precision(I)$  is either 0 or  $1/|output(I)|$ . However, we are not interested in the specific behaviour of the system for a particular case but in the average behaviour of the system. Hence, we are interested in the average recall (i.e., the sum of all recall values divided by the number of cases used) and the average precision. We will represent these averages in our figures, but will use for example the term ‘recall’ when in fact we mean ‘average recall.’

## 5. Results of the degradation study—data input

In this section, we present the robustness results with respect to the data input that we have obtained in empirical experiments with the plant-classification system. First, we will define the input quality measure we will use in Sect. 5.1. Thereafter, we will give results using the ordering on the observables found in the test cases (Sect. 5.2). We analyse the effect of other orderings in Sect. 5.3. We give some conclusions in Sect. 5.4.

### 5.1. Which input quality measure to use?

According to the definitions from Sect. 2, we must still decide on what to use as a measure on the input quality. In this case study, we choose the *completeness of the input* as the measure of input quality. In our classification system, completeness of the input can be directly translated as the *number of available observations*.

There are two reasons why this choice is reasonable and attractive:

**Robustness:** in many practical classification settings, the input observations are not completely available. It then becomes an interesting question how robust the system functions under such incomplete input.

**Anytime behaviour:** Even when all observations are present, there are practical settings where insufficient run time is available to process all the observations: some output from the system is required before a given real-time deadline, and not all observations can be processed before this deadline. Those observations that could not be processed before the deadline can be regarded as ‘missing from the input.’



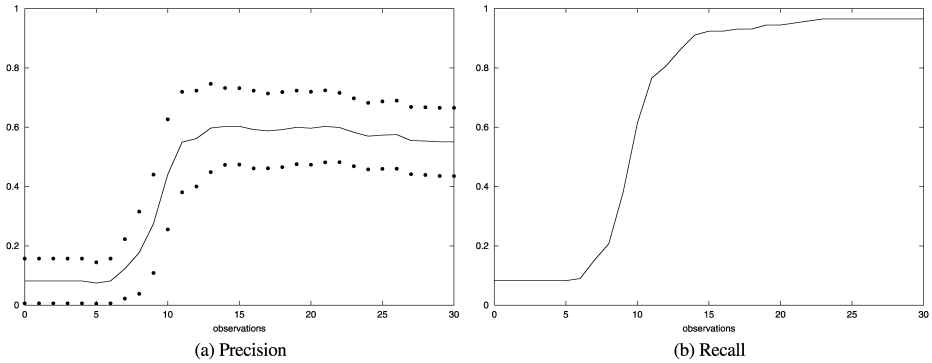


Fig. 3. Measures with test-case order

As a result of this second reason, the degradation results that we present in this section can also be seen as *anytime performance profiles* for the plant-classification system. Performance profiles are a basic tool in the study of anytime algorithms (Dean and Boddy 1988). They plot the output quality as a function of available run time. Because available run time can be interpreted as one aspect of input quality, such performance profiles are simply a special case of our more general proposal: performance profiles only study output degradation as a function of decreased run time, whereas our approach is applicable to any aspect of input quality that one chooses to model.

In the following, we will present a number of graphs analysing the robustness of the plant-classification system. Each of these graphs plot output quality (measured by either recall or precision) against input quality (measured by the number of observations that were available to the system). If one is interested in anytime behaviour, these graphs can be read from left to right: “What happens when the system has time to process more and more of the inputs?” If one is interested in robustness, these graphs should be read from right to left: “What happens when the system is provided with fewer and fewer of the inputs?”

## 5.2. Using the input sequence from the test cases

Now that we have established that the number of available observations will be the input aspect that we will degrade in our studies, we have to decide in which order observations will be made available to the system. Our first choice is simply based on the order in which the observations appeared in the test cases for the plant-classification system. Each such test case consisted of a list of observables and their values for that case. Figure 3a shows how the precision of the answers from the system (as defined in Definition 2.2) increases when longer initial sequences of the test cases were given to the system. The first surprise that this graph has in store for us is its monotonic growth:

**Surprise 5.1.** Both average precision and average recall (see Fig. 3) grow monotonically (or almost monotonically in the case of precision) when adding more observations. This is somewhat surprising because this is not true for individual cases.<sup>4</sup>

<sup>4</sup> This result is not completely surprising because it is well known that the average of several variables can indeed show a different distribution than the individual variables.

The classification algorithm of the plant-classification system assigns both positive and negative scores. This means that the answer set can both grow and shrink when adding more observations. In fact, only 58% of the test cases have a monotonically growing answer set. As mentioned above, such monotonic behaviour is desirable from both a robustness and from an anytime perspective, so on a case-by-case basis, the plant-classification system does not score very well on this. Surprisingly, the average-case behaviour of the system is apparently much better.

A second observation to make is that (as to be expected) initially the system is not able to make any sensible guess at likely solutions (this holds up to about six observations). For higher number of available observations, the graph is surprising for two reasons:

**Surprise 5.2.** After about 12 observations, adding more observations does not increase the precision. This is surprising because most cases contain as much as 19–30 observations. Figure 3a suggests that 12 observations is sufficient to obtain the maximally achievable precision on average.

**Surprise 5.3.** The region in which additional observations actually contribute to an increase in precision is surprisingly small, namely between the 6 and 12 observations. Of the 19–30 observations per case, all observable changes to the output seem to be in this small segment of observations!

Figure 3b shows similar results for the other dimension of output quality, namely the recall from Definition 2.1.

The dotted lines in Fig. 3a indicate the variance of the precision, and this variance is rather significant. It shows that the distribution of the actual precision values that were obtained for the different cases are actually spread rather widely around the average.<sup>5</sup>

Figure 4 gives more insight in the distribution of the precision than the simple average from Fig. 3a. Each line in this figure shows the percentage of cases that achieved a precision of at least a certain value after the given number of observations. The lowest line shows that, after 12 observations, 40% of the cases have already reached the maximum precision (namely 1). Furthermore, and more surprisingly, this percentage then stops growing! This means that:

**Surprise 5.4.** When aiming for the maximum precision of 1, there is no need to use any more than 12 observations (out of a maximum of 30!). If the maximum precision has not been reached after the first 12 observations, adding further observations will not help.

This is actually a more precise version of Surprise 5.2 above. There we claimed that extending beyond 12 observations was not useful *on average*. Here we see that, for harder cases, a few more observations do actually help, although not more than 20 observations in total.

This is because, at the other end of the scale (the top line in Fig. 4), we see that the percentage of cases with a precision of at least 0.2 continues to increase during a longer interval. Apparently, harder cases (those that ultimately achieve a lower precision) benefit more from additional observations than easy cases (those that achieve precision 1). Nevertheless, even there we see that no increase is gained after about 20 observations:

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<sup>5</sup> No variance was plotted for the recall because, as explained earlier, in our application, the recall is either 0 or 1. Because of this, the variance for recall is not a meaningful notion.

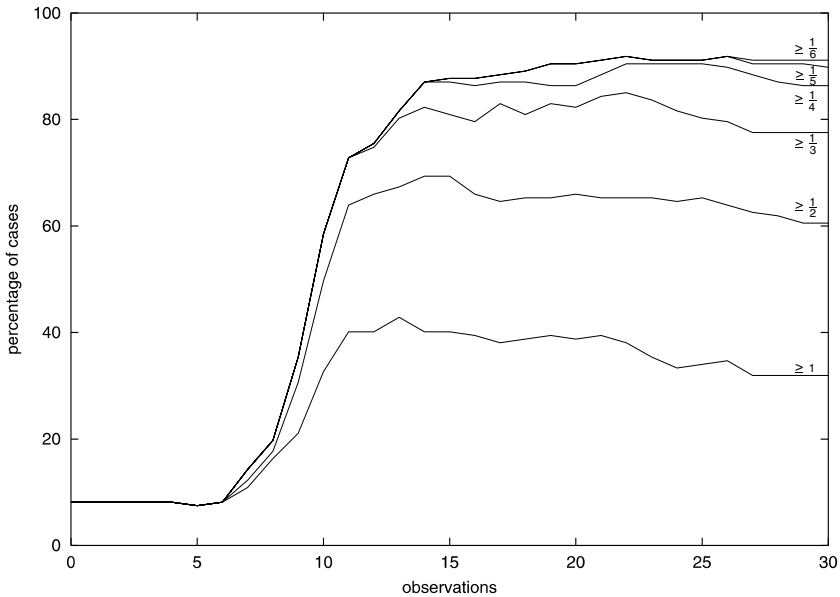


Fig. 4. Precision with multiple levels

**Surprise 5.5.** Whatever the final precision that is ultimately obtained by the system, this level of precision is already obtained after at most 20 observations. It seems that asking for any more than 20 observations will not improve the output quality any further. This is surprising because many cases (in fact 98% of the test set) contain more than 20 observations.

Looking at the initial segment of observations, we see another surprise: although we may expect that a low number of observations leads to a low average precision, it is surprising that the lines for the different precision levels all *coincide* until the sixth observation:

**Surprise 5.6.** No increase in precision can be gained from the first six observations.

This means that, in an anytime setting, interrupting the system before the sixth observation is completely useless because no increase in precision will have been obtained yet.

Figure 4 is particularly interesting from an anytime perspective: it tells us, for each partially processed input, what the chance is that the system has already obtained a certain precision in its output: for instance, after having fed the system ten observations, there is a 30% chance that it has already obtained the maximum precision of 1, a 45% chance that it has already obtained a precision of at least 0.5, and a 60% chance that it has already obtained a precision of at least 0.3.<sup>6</sup> This information can be used by the user to determine if it is useful to continue feeding the system more input or if a sufficiently high precision has already been obtained for the purposes of the user so that processing (and acquiring potentially expensive observations) can be stopped. Our graph (when interpreted as a performance profile)

<sup>6</sup> Note that these chances are cumulative, which is why they add up to more than 100%.

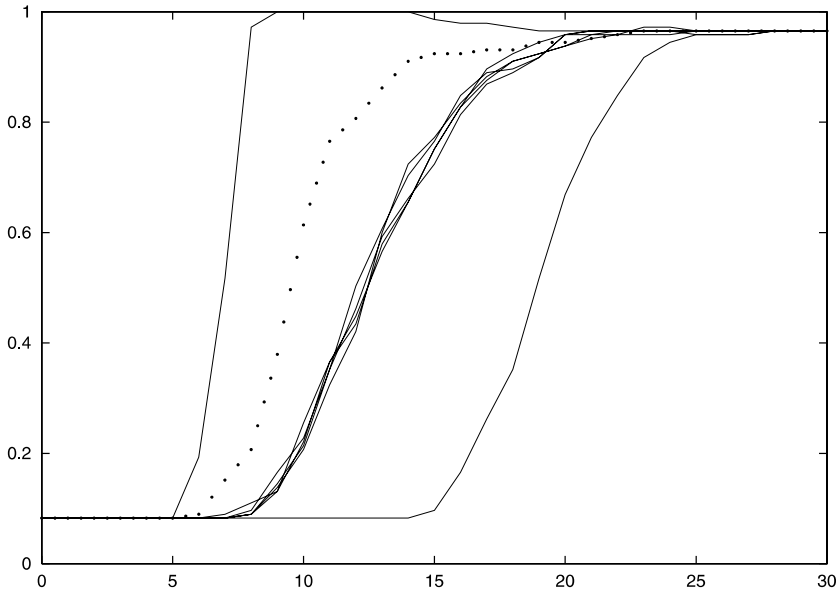


Fig. 5. Recall with various orderings

contains much more information than the usual performance profiles presented in the literature (e.g., Zilberstein 1996). These graphs typically give only a *single* expected value for the output quality at any point in time (compare our Fig. 3a), whereas we give a probability distribution of the expected output value, which is much more informative.

Note that the ideas behind Fig. 4 can in principle also be applied to the recall. We omitted this because, in our case study, the recall is either 0 or 1, thus the resulting figure would be the same as Fig. 3b.

### 5.3. Exploring other input sequences

In the profiles so far, we have degraded the input by removing observations in the order in which they were listed in each test case. Similar degradation experiments were performed using different orderings, which are reported in Fig. 5.

For reference, the dotted line shows the recall profile from Fig. 3b. The leftmost line shows the theoretically optimal average-recall profile: at each step in each case, we computed which next observation would contribute maximally to an increase in recall. This computation can only be done theoretically for test cases where all observations are already present. The rightmost line shows the slowest average-recall profile. Note that every other recall profile must lie between these two lines. Figure 5 also shows a bundle of lines. Each line corresponds with a random ordering. Finally, we also performed experiments with the ordering shown by the graphical user interface (GUI), which is represented by the line close to the dotted line. These experiments lead us to the following observation:

**Surprise 5.7.** The degradation sequence taken from the test cases and GUI is surprisingly effective in obtaining a high recall after only a few observations. In fact,

it is much closer to the theoretically optimal sequence than the randomly generated (information-free) sequences.

#### **5.4. Preliminary conclusions on robustness**

From the first experiment in which we used the test-case ordering, it is clear that the robustness of the plant classification system is not very uniform across the distribution of input quality. When degrading the input quality, the system first appears extremely stable against missing observations, as no quality loss occurs at all. This holds until about 12–15 observation. At that point, the robustness of the system is very low and the input quality drops dramatically.

The experiments with different orderings showed that the plant classification system is very sensitive to the specific order in which the observations are presented to the system, which had effects on the robustness profile obtained. This type of robustness is not covered by our definitions in Sect. 2.4. The definitions there are all concerned with comparing the behaviour of different systems on the same degrading input. The phenomenon observed in Fig. 5 concerns the behaviour of a single system on different ways of degrading the input. We leave it for further research how to include this type of robustness in our approach.

### **6. Results of the degradation study—knowledge base**

The degradation experiments on data input already yielded interesting insights into the behaviour of a realistic KBS. In this section, we will perform the same kind of analysis with respect to the knowledge base used. For the input quality, we will measure the incompleteness and incorrectness of the knowledge base. In Sect. 6.1, we will analyse robustness with respect to an incomplete knowledge base, whereas in Sect. 6.2, we will analyse robustness with respect to an incorrect knowledge base.

#### **6.1. Incomplete knowledge**

Our experiment is as follows: we select some percentage of rules at random from the knowledge base, remove the selected rules and compute the recall and precision value for each case with the modified knowledge base. The average recall (i.e., the sum of all recall values divided by the number of cases) and the average precision will indicate the robustness of the system with respect to the percentage of rules removed. Of course, the experiment has to be repeated multiple times to obtain the robustness of the system on average. Note that, as we are no experts ourselves in plant classification, and therefore are unable to check if some rules are missing from the knowledge base, we will call the provided plant classification system complete, although in reality it may not be.

The results of the experiments are reported in Fig. 6b for the recall and in Fig. 6a for the precision. For each percentage, the average recall and average precision were obtained over ten different runs. Besides average values, the minimal and maximal obtained values are also plotted in both graphs.

Both graphs show an almost smooth decrease of our measured values. The graphs are surprising in that the measures start to decrease around 40% in both graphs.

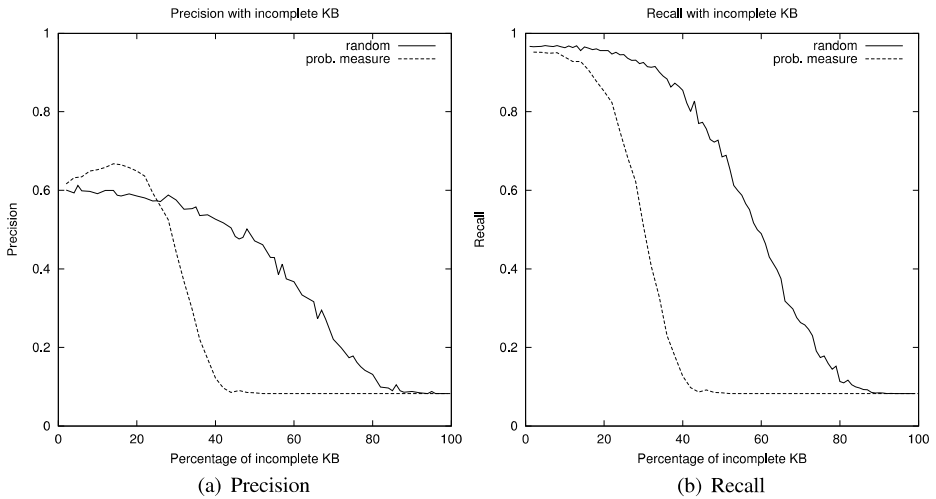


Fig. 6. Recall and precision with incomplete knowledge base

**Surprise 6.1.** In the plant classification system, almost 40% of the knowledge base can be removed at random without severe quality loss.

A possible cause for this decrease at 40% and not at some earlier point is that the average recall and precision are computed over 150 cases. When a rule is removed from the knowledge base, it will only have an effect on a small number of cases and therefore only a small effect on the average recall and precision. When more rules are removed, more cases will be effected, which results in a decreasing recall and precision.

This form of degradation experiment can lead to interesting insights into the robustness behaviour of the system analysed. Nevertheless, the experiment performed has a drawback. It is not realistic to assume that each element in the knowledge base has the same chance of being forgotten. It would be more realistic to remove parts of the knowledge base based on some probability measure. Several measures should be compared when it is not obvious which measure should be used.

In another experiment, we used a probability measure instead of removing rules at random from the knowledge base. Our results with this probability measure are also in Fig. 6. Obviously, the results have changed dramatically. Whereas our previous results (also in Fig. 6) showed that 40% of the knowledge base could be removed without severe quality loss, the new results show that, when 40% of the knowledge base is removed in a biased way, the system becomes useless. Furthermore, the drop in output quality already starts at 15% and is much steeper than before.

These new results should warn people before using the degradation studies for analysing the robustness of KBSs. The experimental setup should be as realistic as possible and care has to be taken when interpreting the results, as these can be sensitive to the chosen setup, as we demonstrated with our case study.

## 6.2. Incorrect knowledge

In our case study, the knowledge base consists of rules. Each rule consists of some observations, a name of a plant and a score. To test the robustness with respect to

incorrect knowledge, the rules need to be modified in some way. However, we like to do this in a realistic setting. Modifying the observations at random is therefore no option. First, some observations are usually answered right while others are prone to errors. Second, if an observation is wrong, it is usually not done at random. Some answers look alike while others are clearly distinct. Modifying the observations of the rules realistically therefore requires domain knowledge, which we lack. However, modifying the score of a rule in our case study does not require any domain knowledge.

In our experiments with incorrect knowledge, we address the question: “How robust is the system for incorrectly entered scores?” Our experiment is therefore as follows: we select some percentage of rules at random from the knowledge base, modify the score of the selected rules, and compute the recall and precision value for each case with the modified knowledge base. The average recall (i.e., the sum of all recall values divided by the number of cases) and the average precision will indicate the robustness of the system with respect to the percentage of rules modified. Of course, the experiment has to be repeated multiple times to obtain the robustness of the system on average.

Only one question remains: “In what way do we modify the score of a rule?” We identified the following parameters:

**Direction:** Scores can be changed to a higher or lower value. Most likely, scores are damaged in both directions. Nevertheless, we also investigate the effect of a biased expert, i.e., an expert who always assesses something too high (or too low). We will use the word positive when scores are only changed to a higher value and the word negative when scores are only changed to a lower value. When both words do not occur, it means scores are changed in both directions.

**Size:** The scores of rules are changed from one class to another. Most likely, the new class is only one higher or one lower than the old class. We will call this kind of damage a near miss. To be complete, we also investigate the effect when the difference of the new class and old class is two classes. We will call this kind of damage an error.

The parameters lead to six different experiments, but before discussing the actual results, let us first consider what results are to be expected.

### 6.2.1. Hypotheses

The plant classification system we are analysing uses a threshold and only gives plants with a score higher than this threshold as output. When we change the scores of rules to a higher value, it follows that the final score of the plants can only increase. As the recall only measures if the correct answer is given as output, it follows that the recall can never decrease. The recall will probably increase as more plants (including the correct answer) are now more likely to cross the threshold and be given as output.

**Hypothesis 6.1.** When the scores of rules are increased, the recall of the system will increase.

The converse also holds. When we change the scores of the rules to a lower value, it follows that the recall can never increase. When the scores are decreased sufficiently, the recall will decrease as outputted plants that are correct will drop below the threshold.

**Hypothesis 6.2.** When the scores of rules are decreased, the recall of the system will decrease.

Some hypotheses for the precision can also be given, but the argument is more complex. Considering the formula for the precision (Definition 2.2), we can identify two causes for an increase in precision:

- I1. The score of the correct plant is increased and thereby crosses the threshold. In this case, the precision changes from 0 to some positive value.
- I2. The scores of one or more incorrect plants decrease and thereby drop below the threshold. If the correct answer remains in the output, this will increase the precision from some positive value to a higher positive value. For example, let A and B be two plants given as output. Let A be the correct plant. In this case, the system will have a precision of  $1/2$ . When the scores are changed such that B drops below the threshold while A remains above the threshold, the precision will change to 1.

In a similar way, we can identify two causes for a decrease in precision:

- D1. The score of the correct plant drops below the threshold. The precision changes from a positive value to 0.
- D2. The score of one or more incorrect plants increase and cross the threshold.

When we change the scores of rules to a higher value, both I1 or D2 can occur. However, I1 is unlikely, as previous experiments showed that the recall of the system is already close to the optimal value of 1. It follows that we expect a decrease in precision.

**Hypothesis 6.3.** When the scores of rules are increased, the precision of the system will decrease.

When we change the scores of rules to a lower value, both I2 or D1 can occur. As these causes change, the precision into two different directions it is not obvious to predict the outcome of the precision.

The outcome is even harder to predict when we change the scores of rules both to lower values and to higher values, as all four causes for the change in precision can occur. Also the recall can now both increase and decrease and is therefore harder to predict. Nevertheless, for the recall, we know that the performance profile has to lie somewhere between the results for the strictly positive and negative changes.

**Hypothesis 6.4.** When some rules are changed positively while other rules are changed negatively, the recall of the system will be between the recall values of the strictly positive and negative changes.

Besides direction of changes, we will also look into the effect of the size of the changes. We expect that a larger change will have a larger effect on the average values. For example, when the scores are changed positively and the recall increases with near misses, we expect the recall to increase even more when we experiment with positive errors.

**Hypothesis 6.5.** When comparing experiments in which we make errors instead of near misses without changing the direction of the changes, the effect observed in the near-miss experiment will be made stronger.



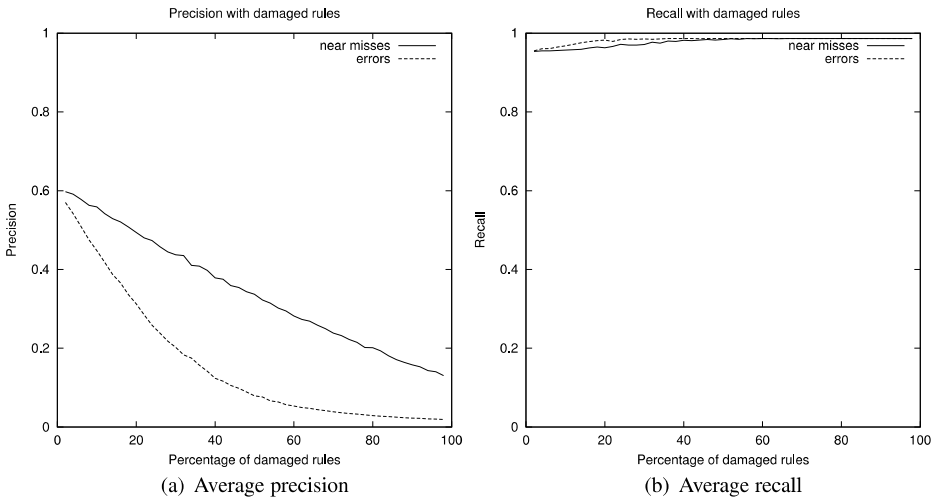


Fig. 7. Positive near misses and positive errors

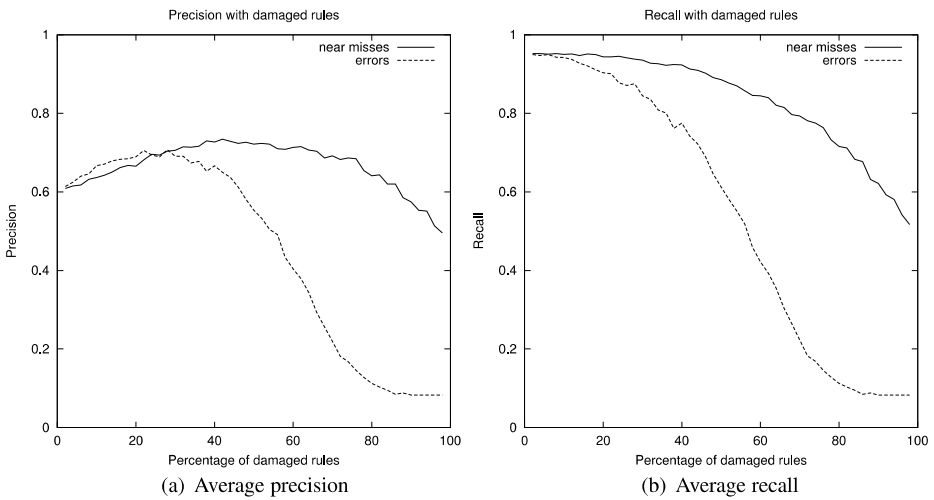


Fig. 8. Negative near misses and negative errors

### 6.2.2. Results

Now we will discuss the results, which are shown in the Figs. 7 through 9.

First note that our hypotheses hold in the shown figures. In the case of positive Changes, the recall increases as is shown by Fig. 7b (Hypothesis 6.1). In the case of negative changes, the recall Decreases, as is shown by Fig. 8b (Hypothesis 6.2). In case of positive changes, the precision Decreases, as is shown by Fig. 7a (Hypothesis 6.3). In case of near misses, the recall (Fig. 9b) will lie between the values found in the strictly positive experiment (Fig. 7b) and the strictly negative experiment (Fig. 8b). The same holds for the experiments with errors (Hypothesis 6.4). In case of positive changes, we find that the recall in the experiment with errors lies

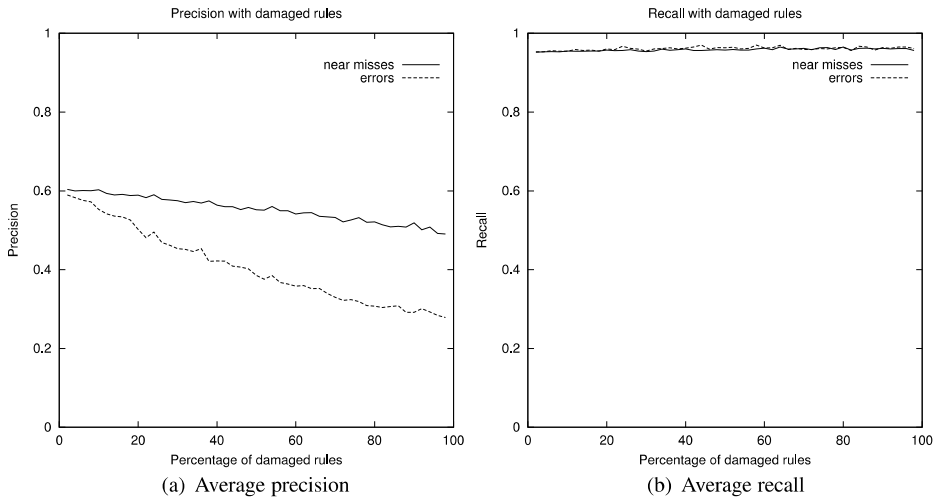


Fig. 9. Near misses and errors

everywhere above the recall in the experiment with near misses (Fig. 7b). In the case of negative changes, we find that the recall in the experiment with errors lies everywhere below the recall in the experiment with near misses (Fig. 8b) (Hypothesis 6.5).

Other points of interest are the specific curves we obtained in our experiments. For example, in the case of positive near misses (Fig. 7a), we find a *linear* decrease in precision whereas the decrease is *nonlinear* when we increase the size of the changes.

In the case of negative near misses, we could not predict the behaviour of the Precision, as there are two causes that could change the precision in opposite directions (causes I2 and D2 discussed in Sect. 6.2.1). Figure 8a tells us that I2 happens more often than D1 in the first segment of the figure as the precision increases. Hence, in most cases, first some incorrect plants drop below the threshold before the correct plant drops below the threshold. It follows that, in most cases, the correct plant has outscored most of the incorrect plants, which is the desired behaviour of the system.

The same curve as in negative near misses also occurs in the figure for negative errors (Fig. 8); however, the curve of the negative near misses is compressed into the first half of the figure because the size of the changes has increased. Note that this holds for both the precision and the recall.

Besides interesting behaviour, we are of course interested in the robustness of the system. Probably the most realistic setting is the experiment with near misses (Fig. 9). Both precision and recall show a very stable curve, indicating a robust knowledge base for near misses. Although the knowledge base appears to be robust on the entire range of the x-axis, from a practical point of view, usually only the first part of the figure is important.

## 7. Conclusions

In this paper, we have argued for the need for *quantitative analysis* of the quality of KBSs. In particular, we have shown how *robust behaviour* in the light of

incomplete system input as well as an incomplete and incorrect knowledge base is amenable to such quantitative analysis. Our quantitative analysis is based on the idea of *degradation studies*: analyse how the quality of the output changes as a function of degrading input. We have proposed a set of *general definitions* that are general enough that they can be used in similar degradation experiments by others, even if the systems concerned are of a very different nature than the one in our case study. We have shown the practicality of our approach by applying it to a particular *case study*. This yielded a number of surprising insights into the behaviour of the system under study.

We believe that the following issues are the most important in our proposed approach of degradation studies for measuring the robustness of KBSs:

**Generality:** Degradation studies are general enough to be applicable to many KBSs.

The output quality is measured using the recall and precision, which are well known in information retrieval. Furthermore, the general concepts of incompleteness and incorrectness can usually be used as measures for the quality of the input.

**Insights:** Degradation studies provide insights into the behaviour of the system analysed. As we demonstrated in our case study, this includes its anytime performance with respect to incomplete data or its robustness with respect to incomplete or incorrect data or knowledge.

**Performability:** The degradation study we performed could quite easily be performed. We were able to do this because we had easy and quick access to the KBS (i.e., giving input to the system and reading its output by an external program). Furthermore, programs could be used to modify the input and knowledge base in a controlled way. These conditions should not be too hard to realize for many other KBSs.

**Setup:** Before performing a degradation study on a KBS, one should carefully consider the experimental setup. The way data or knowledge is removed or modified may greatly influence the outcome of the degradation studies.

The ultimate suggestion that follows from this work is that any KBS should, upon delivery, come accompanied with a set of degradation statistics such as discussed in this paper as a quantitative way of measuring interesting and important aspects of the systems quality. This would contribute to a more empirical and quantitative analysis of AI systems in general and of KBSs in particular, very much in the spirit of Cohen (1995).

## 8. Future work

Although the results above already yield interesting insights in the behaviour of a realistic KBS, many other aspects could still be uncovered using further degradation studies. We discuss some of these extensions in this section:

The informal definition for robustness that we used as a starting point in Sect. 2 has not been carried through entirely in the paper. Functioning correctly in the presence of invalid inputs has not been evaluated in the case study and should be included in future research.

Zilberstein (1996) suggests a category of measures on output quality that is not yet covered by the recall and precision that we have used in the above, namely specificity of a solution. This is intended to represent the degree of detail in the system's answer. An example would be a system that can compute names of ever finer grained

plant families instead of only individual species (as above). This property was irrelevant in our case study because the plant-classification system only deals with a flat list of candidates, not with a hierarchically organized space of candidates. We have therefore ignored this potential third dimension of KBS output quality, but we expect that good measures can be devised for this just as well as for the other two dimensions that we did handle.

The output quality measures we used (precision and recall) are geared towards systems with a discrete output (a set of answers). Some KBS applications return real-valued answers (e.g., ratings). We must study how these systems can also be subjected to degradation studies using acceptable measures. In fact, the plant-classification system not only returns a set of candidates, but indicates a numeric score for each candidate. Our current output measures completely ignore this score. A further step would be to also include this score in the quality measures.

As mentioned in Sect. 5.2, Fig. 4 can be interpreted as a prediction for the expected quality of the output after a given number of observations. In effect, Fig. 4 is the result of *learning the anytime performance profile* through the test cases. As with any learning task, we can apply cross-validation to the set of test cases (Cohen 1995): use a subset of the test cases to learn profiles as in Fig. 4 and use the remaining cases to check the accuracy of the predicted performance levels.

Our measures for output quality (recall and precision) can only be computed for cases where the correct answer is actually known. This is not as obvious as it may sound. In many applications (e.g., computing the best solution to a design problem) the correct (i.e., best) answer is not known to any human expert. In such cases, one must either resort to known approximations of the correct answer or fundamentally different quality measures must be defined.

Our proposed definitions for output quality (precision and recall) focus on the correctness of the answers computed by a system. Of course, there are many more aspects to the quality of a KBS, such as the quality of its explanation, its computational efficiency, its interaction with its environment (be it users or other systems), etc. It is an open issue to us whether the same 'degradation-study approach can be taken to quantifying any of these other aspects of the systems quality.

**Acknowledgements.** We would like to thank Frank Puppe for the help he has given us. This paper was inspired by a discussion with him during the Banff'98 KAW workshop. He gave us access to the plant-classification software and explained in detail its working. He was also always available to answer any question by e-mail.

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