# QDES: Quality-Design Expert System for Steel Products

*Yoshiteru Iwata and Norio Obama*

Meeting customer demands for higher quality is a major business focus in the development of steel products. The quality of steel can be increased in many ways, for example, by improving its toughness or its resistance to atmospheric corrosion or by making thinner sections without sacrificing strength.

As the largest steel supplier in the world, Nippon Steel Corporation (NSC) receives many kinds of customer requests for new steel products with increased quality, sections of different size, and so on. Customer requests have become more complex, and their quality requirements have increased. At the same time, quality-design experts are expected to decrease the time to judge whether production of a desired product is possible and to design the product. Furthermore, fewer quality-design experts are available to design the new products.

Problems in the quality design of steel products have become important. To deal with these problems, NSC developed a design support system with a production database and a retrieval mechanism. Unfortunately, this system was efficient only for the design of products that were similar to products produced in the past. To overcome the limitations of the design support system, NSC undertook the challenge of developing the quality-design expert system (QDES). QDES is fully opera-

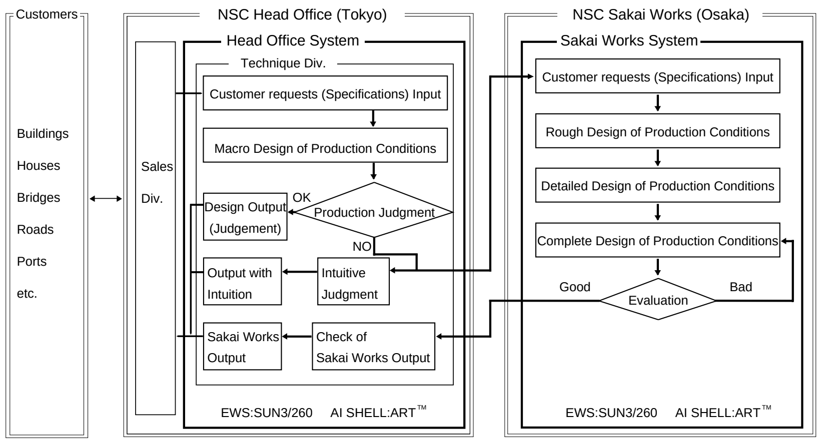


*Figure 1.* QDES *Architecture.*

tional and provides valid designs for shaped-steel products.

The application of AI to design problems is generally considered difficult in terms of knowledge acquisition and system modeling because of the combinatorial explosion that is inherent in a problem with a huge solution space. The achievement of QDES is a milestone in the application of AI to design. This chapter analyzes the experts' quality-design process and presents the technical points required to create the expert system model.

## QDES Architecture

QDES runs on Sun engineering workstations within the ART environment and is integrated with the UNIFY database tool. QDES consists of about 3,000 rules, and about 500,000 lines of code. The system requires about 100 megabytes during run time.

QDES consists of two interconnected systems, as shown in figure 1: the head office system and the Sakai Works system. (Sakai Works is one of NSC's steel plants.) When specifications for a new product are input to QDES, the system assesses whether the product can be produced; if so, it creates a plan for the design, including operation conditions and cost.

The head office system performs an initial screening. When this system judges that a detailed design is needed, it transfers the product specifications to the Sakai Works system. The Sakai Works system develops a detailed design using many kinds of detailed data, for example, process data and test data. This system is able to design more complicated products than the head office system.

QDES performs the following functions: (1) system control, (2) reasoning, (3) maintenance, (4) explanation, (5) drawing management, (6) intelligent man-machine interaction, and (7) correspondence. The system-control function supervises the other functions and maintains coherence among them. Because the main function is reasoning, this chapter concentrates on the reasoning process.

Customer requests are primarily classified into two types: (1) requests for products made of a new material and (2) requests for H sections with new dimensions. (An H section is illustrated in figure 7.) For either type of request, the input to QDES includes information about the customer, the type of steel product, how and where the product will be used, and the deadline by which the customer needs results from QDES. Additional input for a request for a new material includes tensile strength; yield strength; yield point; elongation; temperature of charpy impact test; energy of charpy impact test; welding conditions; electric resistance; and upper and lower limits for the amounts of various ingredients, such as C, Si, Mn, P, S, Cu, Ni, Cr, Mo, Nb, V, Al, and Ti. Additional input for a request for an H section with new dimensions is flange height, web width, thicknesses of the web and the flange, corner radius of the shaped steel, length, quantity, weight, size accuracy tolerance, bending conditions, and squareness.

The customer requesting a new steel product provides the input data previously described. Using these data, QDES designs the operating conditions and assesses the ability to produce the specified product. The input to the Sakai Works system is the same as the input to the head office system.

## Analysis of the Experts' Design Process Model

Prior to the development of the expert system, the design process of the human experts was thoroughly analyzed.

The experts at the head office go through the following four design stages: (1) macro design of production conditions, (2) production assessment, (3) intuitive judgment (for new materials only), and (4) check of Sakai Works output. Figure 1 shows the flow of control among these four stages.

In stage 1 (macro design of production conditions), the experts determine the essential issues based on input from customers, select the most similar past case, use parameters from this case in the initial design, and design the operating conditions without the local detailed knowledge of the plant where the product will be produced.

In stage 2 (production assessment), the experts judge production to be possible when they are able to design the operating conditions. If they are unable to design the operating conditions, the experts cannot judge whether production is possible. In such cases, they transfer the customer's input to the experts at Sakai Works.

Experts proceed to stage 3 (intuitive judgment) for a new material request when they are unable to judge whether the product can be produced, but a prospective customer needs to know whether the material can be produced. In this situation, the experts make intuitive judgments about whether the new material can be produced.

If the experts at Sakai Works are asked to design the operating conditions and judge whether the product can be produced, the experts at the head office go to stage 4 (check of Sakai Works output). In this stage, they check the output produced by the experts at Sakai Works.

The experts at Sakai Works go through the following four design stages: (1) rough design of production conditions, (2) detailed design of production conditions, (3) complete design of production conditions, and (4) evaluation. The flow of control among these stages is shown in figure 1. The experts' actions in each stage depend on whether the product is a new material or an H section with new dimensions.

For a new material, in stage 1 (rough design of production conditions), the experts determine the essential issues based on the input, select the most similar past case, and use parameters of this case as parameters of the initial design for the method of production. There are many parameters of the method of production, for example, whether the product needs continuous casting or ingot casting and whether it needs heat treatment.

In stage 2 (detailed design of production conditions), the experts design by quoting the test results from the most similar case. They use uncertain knowledge to evaluate whether the material can be produced given the charpy impact specification.

In stage 3 (complete design of production conditions), the experts use the ingredient combinations from the most similar cases. The customer specifications include acceptable ranges for the amounts of various ingredients. The experts decide what amount of different ingredients to use after trying as many combinations (within the acceptable limits) as possible.

In stage 4 (evaluation), the experts consider the production stability and judge whether the material can be produced. If the experts are able to design operating conditions, they judge production to be possible. If not, the experts then select the next most similar past case and investigate a different method of production based on this case. If the experts are not able to design the operating conditions after all alternative design methods are tried, they judge production to be impossible.

For an H section with new dimensions, in stage 1 (rough design of production conditions), the experts interpret the essential issues of the input and perform an initial screening. They judge production possible when the dimensions are within the range of dimensions of past products. When the new dimensions are outside this range, the experts select the most similar past case and use the parameters of this case as the parameters of the initial design. The production method for H sections is rolling. There are many conditions of the rolling operation, for example, vertical roll shape and horizontal roll shape.

In stage 2 (detailed design of production conditions), the experts design by quoting the conditions of the rolling operation from the most similar case and design the schedule of rolling passes, the mill spring, the shape of slab, and so on. At this stage, they consider conditions such as the number of passes through each rolling mill and the vertical and horizontal roll gaps of each rolling. The Sakai Works rolling process has 7 rolling mills. The experts design the pass schedule of each rolling mill by modifying the rolling conditions from the past case so that rolling will produce a product with the desired dimensions. If the experts cannot design the rolling pass schedule despite considering all alternative rolling pass schedule design methods, they judge production to be impossible.

In stage 3 (complete design of production conditions), the experts use other rolling conditions from the most similar case and modify them so that rolling will produce a product with the desired dimensions. At this stage, the experts consider conditions such as cooling conditions, rolling time, and rolling speed.

In stage 4 (evaluation), the experts simulate the vertical rolling load, the horizontal rolling load, rolling temperature, rolling length of each mill rolling pass, and so on, and judge the possibility of production. If the experts are able to design operating conditions, they judge production to be possible. If not, the experts then select the next most similar past case and investigate a different method of production based on this case. If the experts are not able to design the operating conditions after all alternative design methods are tried, they judge production to be impossible.

As previously described, the expert design process consists of various types of reasoning: (1) design based on the most similar past case, (2) consideration of as many alternative combinations of ingredients as possible, (3) intuitive judgments, (4) evaluations with uncertain knowledge, and (5) learning by experience.

### Design Based on the Most Similar Past Case

Experts do not design based on theories only. Often, experts design based on past cases, in particular, the most similar case. In other words, experts use parameters of the most similar case as the initial parameters of a new design.

Experts can judge or design new cases using only theories. Why do experts design with past cases? The designs for past cases were created from a collection of many backgrounds, theories, and techniques. Often, experts can design more easily and more quickly when they use past cases.

Developing a design from first principles typically requires enormous cost and effort; these requirements can be reduced when a design is based on the designs of past cases with many pieces of potentially relevant information. The key issue for this type of reasoning is how to evaluate the similarity between new specifications and the past cases.

### Consideration of as Many Alternatives as Possible

When experts are presented with acceptable ranges for several ingredients, they do not consider all possible combinations of different amounts of each ingredient. They do, however, try to consider as many combinations as possible, so they can design the optimum plan for new specifications. For this type of reasoning, it is important to know how to combine all feasible amounts of the various ingredients within the specified limits and to select the optimum plan from various points of view. It might be possible to build a system that is able to design better plans than the experts because the system can consider more combinations than the expert can.

### Intuitive Judgments

Sometimes, the experts at the head office have to promptly judge the possibility of production for salespeople—before a detailed design is developed at Sakai Works. Hence, the expert often designs by intuition. The intuition is not clear enough to incorporate into an expert system; accordingly, the issue is how to represent the intuition and seek the answer.

### Evaluations with Uncertain Knowledge

Experts often design efficiently while they reason with imprecise measurements, such as “small” or “rather big.” The knowledge is not always exact enough to be put into an exact rules. The issue for reasoning with uncertainty is how to represent the uncertain knowledge and judgments.

### Learning by Experience

Experts do not always have enough knowledge to design. They learn

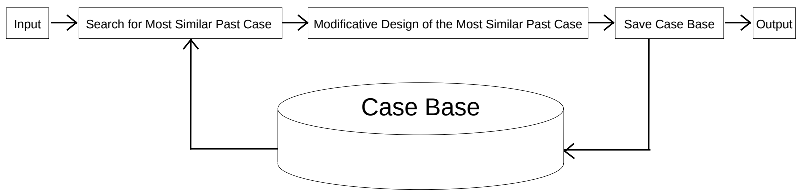


*Figure 2. Case-Based Reasoning in* QDES.

day by day and design the best plan given the current state of their knowledge. Experts try to acquire new useful knowledge to enable them to design for more complicated specifications they might receive.

The main issues are how to develop the acquiring function for getting the useful information, how to efficiently modify the knowledge, how to incorporate new knowledge into an existing knowledge base, how to assure the correctness of the knowledge, and how to keep the knowledge consistent.

## Creation of the Reasoning Model

This section discusses the development of the QDES system in light of the five reasoning methods just presented.

### Design Based on the Most Similar Past Case

QDES uses case-based reasoning (Schank 1982) because the experts themselves develop designs by adapting designs from similar past cases. Furthermore, a more conventional approach, such as ruled-base reasoning, might prove to be infeasible for a problem with such a huge solution space. Figure 2 illustrates how QDES uses case-based reasoning.

The most important issue for a system that uses case-based reasoning is how to evaluate the similarity between the past cases and new specifications. The similarity should be made clear through many interviews with the experts. For example, when the experts design H sections with new dimensions, they evaluate the similarity of the ratio of the flange thickness and the web thickness of the new specifications and past cases.

Case-based reasoning makes the system reasonably compact and, thus, is one of the most important techniques used in QDES. The number of rules is far fewer than if the system had been constructed using only theoretical rules, and the description of the design world is far smaller. Reasoning time is far shorter, and maintenance of the rules and the description is much easier. The efficiency of case-based reasoning is significant in QDES.

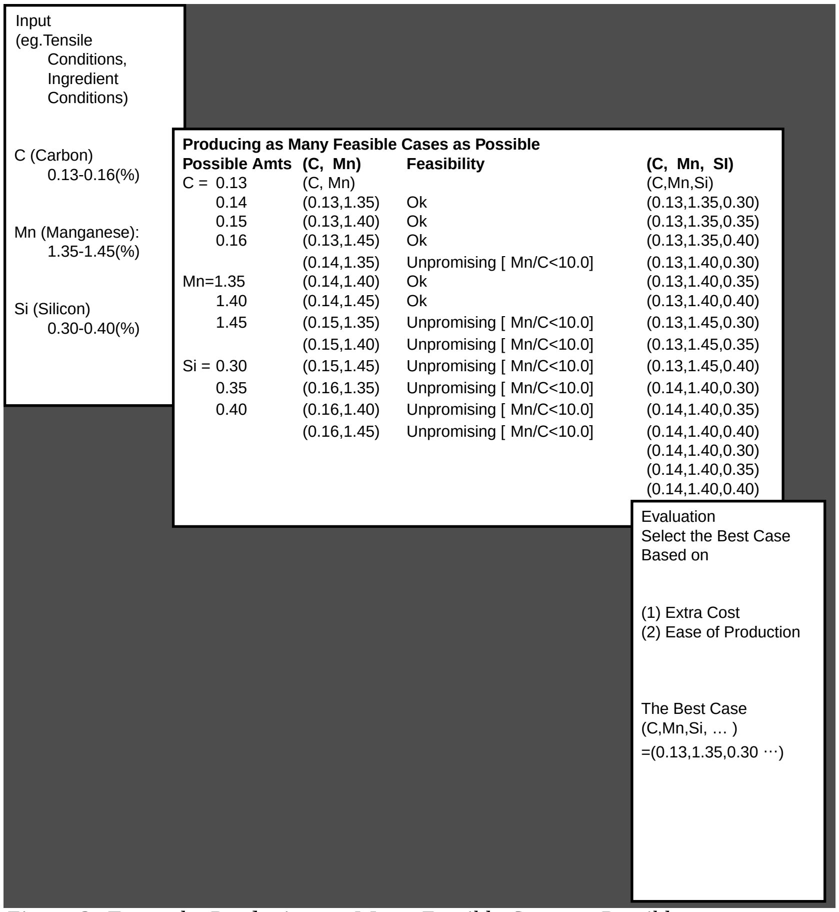


*Figure 3. Example: Producing as Many Feasible Cases as Possible.*

## Consideration of as Many Alternatives as Possible

In stage 3 (complete design of production conditions) at the Sakai Works, the experts design the best combination of ingredients for a new material. They consider the most feasible combination in which the amount of each ingredient is within the specified limits. The experts do not try all combinations of possible amounts of each ingredient. They reject unpromising combinations along the way efficiently using an evaluating function of welding and design. Therefore, the issue is how to build a suitable structure that efficiently tries as many feasible combinations as possible.

To consider a large number of alternatives, hypothetical reasoning is a suitable technique. A more conventional approach might be to generate all possible combinations, evaluate each combination, and reject unsuitable ones. This approach would not be efficient. Instead, QDES uses the hypothetical reasoning capabilities of the ART environment. QDES recognizes unpromising partial combinations and does not expand these into complete combinations.

For example, figure 3 illustrates a request for a new material that must contain 0.13 to 0.16 percent of carbon, 1.35 to 1.45 percent of manganese, and .3 to .4 percent of silicon. (For simplicity, the required proportions of other ingredients are not shown.) QDES combines 4 different levels of carbon with 3 different levels of manganese to produce 12 partial combinations. Rather than combining each of these 12 carbon-manganese combinations with the 3 different levels of silicon, QDES evaluates the particle combinations. It eliminates 7 combinations in which the ratio of manganese to carbon is less than 10.0. QDES then proceeds to combine each of the 5 remaining carbon-manganese combinations with the 3 different silicon levels. This process continues until all ingredients have been added. After each ingredient is added, the partial combinations are evaluated. Only successful partial combinations are combined with the next ingredient.

The experts consider as many combinations as possible but not all combinations. Because QDES can consider more combinations, it can design a better plan with hypothetical reasoning than the experts can.

### Intuitive Judgments

When a prospective customer has a request for a new material, the salesperson asks the experts at the head office whether the material can be produced. Sometimes, the experts must provide an answer before the detailed design is developed at Sakai Works. The experts must use their intuition to make the judgment. For this type of reasoning, the issue is how to represent the intuition and judgments.

The suitable structure of representation, judging, and learning with intuition is based on neural networks (Rumelhart, McClelland, and PDP Research Group 1986). In using a neural network, the main issue is the design of the network structure. The elements of the network, which are based on judgments, have to be obtained through interviews with the experts. When the experts judge the possibility of production, they consider the thickness of steel, the temperature of the charpy impact test, and the tensile strength. Hence, the thickness, the temperature, and the tensile strength are input conditions.

The network structure has to be developed by learning from training cases that contain input data and the experts' output judgments. Analysis of the results of some training cases showed that a three-layered

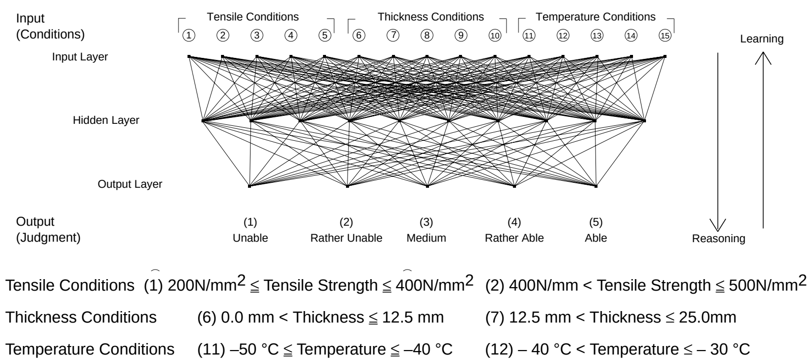


*Figure 4. Neural Network Model of Judgment in QDES.*

network with a back-propagation algorithm is suitable. The network is shown in figure 4. When the number of layers was increased or decreased, the results of the training cases were worse. The optimal number of the hidden layer elements was found to be 10; when the number was increased or decreased, the results of the training cases were worse.

The neural network enables the system to reason with correlations that cannot be represented by exact rules. Although the technique cannot yield precise judgments, it is efficient for making rough judgments in such cases as described. The neural network approach is suitable for judgments in which there are no logical connections between input and output, the input and output are well defined, the patterns of input and output are limited to the cases that the system has experience with, and exactness is not required.

The limitation of this approach is generally a lack of accuracy in generating the output. Because the reasoning model is a black box to the experts, tuning it is difficult. Tuning the model can be accomplished only by teaching the system with new cases. The system can reason perfectly only in a case with the same patterns as a case that the system experienced. In QDES, a neural network was used only for stage 4 of the head office system (intuitive judgment) because more accurate reasoning models were applicable in other stages.

## Evaluations with Uncertain Knowledge

The experts at the Sakai Works use sample test results to determine the steel plant's ability to produce steel with particular charpy impact specifications. Their decisions use imprecise classifications of the test results. For example, a change in temperature can be "small," "rather small," "medium," "rather big," or "big." Their decisions are also uncertain; they rate their ability to produce the desired steel product as “unable,” “rather unable,” “medium,” “rather able,” and “able.” The issue for this type of reasoning is to develop a representation of these imprecise term expressions and a reasoning technique that is acceptable to the experts.

The suitable framework for reasoning with uncertainty is based on the fuzzy model (Zadeh 1965). In using the fuzzy model, the main implementation tasks are the fuzzy membership functions and the fuzzy reasoning mechanism. From an analysis of the experts’ design process, the fuzzy membership functions were determined as shown in figure 5. Both premise parts and consequence parts of judgment rules have fuzzy membership functions corresponding to the experts’ imprecise classifications of test data and uncertain decisions.

When the experts judge the ability to produce steel with new toughness specifications, they first consider a test temperature difference between a past case and the new specifications. They use inexact guidelines such as the following:

> If the temperature difference is big, then production possibility is able.
> If the temperature difference is rather big, then production possibility is rather able.

As figure 5, part 1, shows, a temperature difference of 14° C is rated as “big” with a strength of 0.4 and “rather big” with a strength of 0.6. The first rule uses the strength of “big” to rate production possibility “able” with a strength of 0.4. The second rule uses the strength of “rather big” to rate production possibility “rather able” with a strength of 0.6. Figure 6, part 1, shows that the peak of the membership function for “able” is 0.4. Figure 6, part 2, shows that the peak of the membership function for “rather able” is 0.6. Figure 6, part 3, shows the composition of the two membership functions. The center of gravity for the combined function is plus, so the final judgment is “able.”

The fuzzy model permits effective reasoning with imprecise rules. QDES was able to use the fuzzy model for this reasoning task because the experts make logical (though imprecise) connections between the input data and the output conclusions. Without such logical connections, QDES would have needed to use a neural network, as described earlier. The fuzzy model is preferable to a neural network because the reasoning model can be understood by experts.

## Learning by Experience

When the experts at Sakai Works judge the plant’s ability to produce an H section with new dimensions, they perform an initial screening of the flange thickness, the web thickness, and the ratio of these two

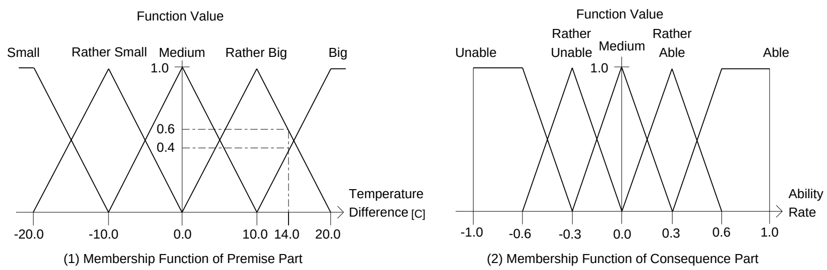


*Figure 5. Examples of Fuzzy Rule Membership Functions.*

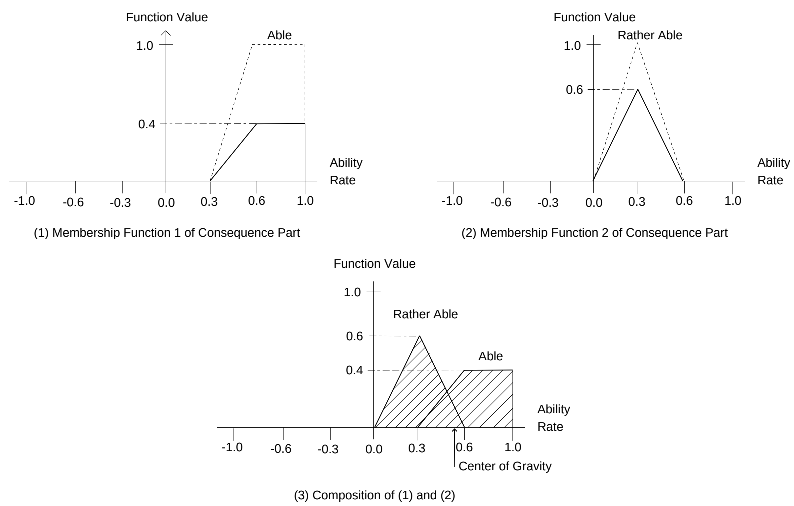


*Figure 6. Examples of Fuzzy Reasoning.*

thicknesses. If the new dimensions are within the range of dimensions of past products, the experts can easily judge that the new section can be produced.

If new specifications fall outside the range of the experts' experience, however, the experts develop a detailed design by adapting the design of similar past cases. When they are able to design production conditions for the new specifications, they expand the range of dimensions that they will use in the initial screening in the future (figure 7).

In a similar manner, QDES learns by experience. The learning model reduces design time by increasing the number of specifications that can be accepted in the rough design stage without the development of

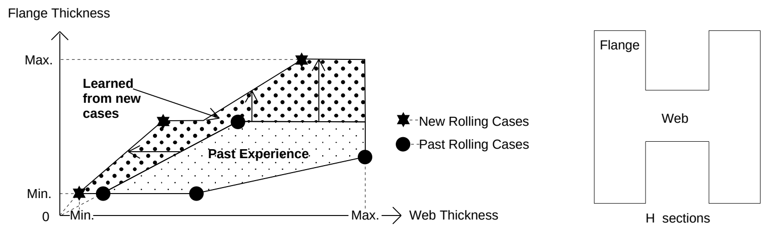


*Figure 7. Learning Model of Judgments in Rolling Production.*

detailed designs.

## Support Functions

Although the main function of QDES is reasoning as described, its support functions are also important. This section describes two representative support functions: maintenance and explanation.

### Maintenance Functions

QDES has two automatic maintenance functions. The first modifies the knowledge used in the rough design stage of the Sakai Works system to enable the system to learn by experience, as described earlier. The second maintenance function automatically adds new production cases to the collection of cases used for case-based reasoning. This function reduces design time but also increases the accuracy of design because the system has a wider range of similar cases to use. Both automatic maintenance functions operate frequently and save the daily maintenance work of the system operators.

QDES also has an interactive maintenance function that the system operators can use to update knowledge when the production process changes, when the standards are updated, and so on. The system operator checks, corrects, and accumulates data displayed by QDES. No updates have been needed since QDES has been in practical use, so this maintenance function has not been used yet.

### Explanation Functions

QDES has two explanation functions. The first gives static, precoded explanations. The second generates explanations dynamically. These explanations trace the system's reasoning process and show how to develop designs. The explanations are shown in natural Japanese language; the system can be used as a valuable training aid for persons not already proficient in quality design.

## Results

QDES was put into operation 18 months after knowledge acquisition began. About 350 person-months were required for development.

QDES has been in practical use since May 1990, and to date, no significant problems have been reported. NSC receives about 20 customer requests each month for shaped-steel products, and QDES designs all these products. QDES is currently running well, and the design space continues to expand. The payoffs are as follows:

First, QDES has reduced the design cycle time by 85 percent. The head office system takes about 20 minutes to design the production conditions and judge whether production is possible. The Sakai Works system takes about 40 minutes for a new material request and about 20 minutes for a request for an H section with new dimensions. This reduction in time allows NSC to accept more business, for example, steel products for multistory buildings and ocean platforms.

Second, the accuracy of design is 30 percent better than with the conventional method. For example, the use of hypothetical reasoning optimizes the combination of ingredients in a new material, thereby reducing the cost of the included ingredients.

Third, the more production experience that QDES acquires, the better the plans are that QDES produces. As described under Maintenance Functions, the system automatically learns from new production cases and collects new cases for use in case-based reasoning.

Fourth, QDES can particularly aid the novice who might not have a good working knowledge of quality design; it provides on-the-job training at the same time.

Fifth, QDES can serve as a resident expert, on hand 24 hours a day, 7 days a week.

QDES provides significant results and benefits in the quality design of steel products. QDES allows NSC to save or earn approximately $200,000 each year. QDES has the potential for tremendous savings in virtually all quality product design.

NSC is currently expanding QDES in two directions: QDES is being transferred to the other NSC Works, and it is being extended to assist with the design of new types of products. QDES will provide a much larger payoff in the near future.

## Conclusions

This chapter presented the QDES approach to system development, which consists of the analysis of experts' quality-design process and the creation of a reasoning model consistent with the experts' planning process. It is important to build a system that is fit to experts. As a consequence, the thorough analysis and the development of knowledge representation and reasoning similar to experts' were crucial to the success of QDES.

The experts' design process uses various types of reasoning, so it is particularly important to combine the appropriate technologies for each type. This approach was effective in building QDES.

Although design applications are generally considered difficult to implement, QDES provides a useful framework for design applications. The main component of case-based reasoning is augmented with various other AI technologies to model the experts' reasoning: Hypothetical reasoning enables the system to generate and evaluate alternative combinations of ingredients, fuzzy modeling provides the mechanism for reasoning with uncertain knowledge when logical connections exist between input and output, and the neural network supports reasoning with intuition when no logical connections exist between input and output.

## References

Rumelhart, D. E.; McClelland, J. L.; and the PDP Research Group. 1986. *Parallel Distributed Processing*, volumes 1 and 2. Cambridge, Mass.: MIT Press.

Schank, R. C. 1982. *Dynamic Memory: A Theory of Reminding and Learning in Computers and People*. Cambridge: Cambridge University Press.

Zadeh, L. A. 1965. Fuzzy Sets. *Information and Control* 8: 338–353.